Charm and Beauty Physics at Fermilab

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Fermilab

International Conference on Flavor Physics

Zhang-Jia-Jie, Hunan, P.R. China

1. Introduction
2. $D^0 \leftrightarrow D^0$ Mixing and DCSD
3. Some Dalitz plots.
4. A few lifetimes.
5. $\Xi_c^+ \rightarrow pK^-\pi^+$
6. P-wave charm.
7. B Physics at the Tevatron.

June 4, 2001

http://home.fnal.gov/~kutschke/talks/Misc/icfp01.pdf

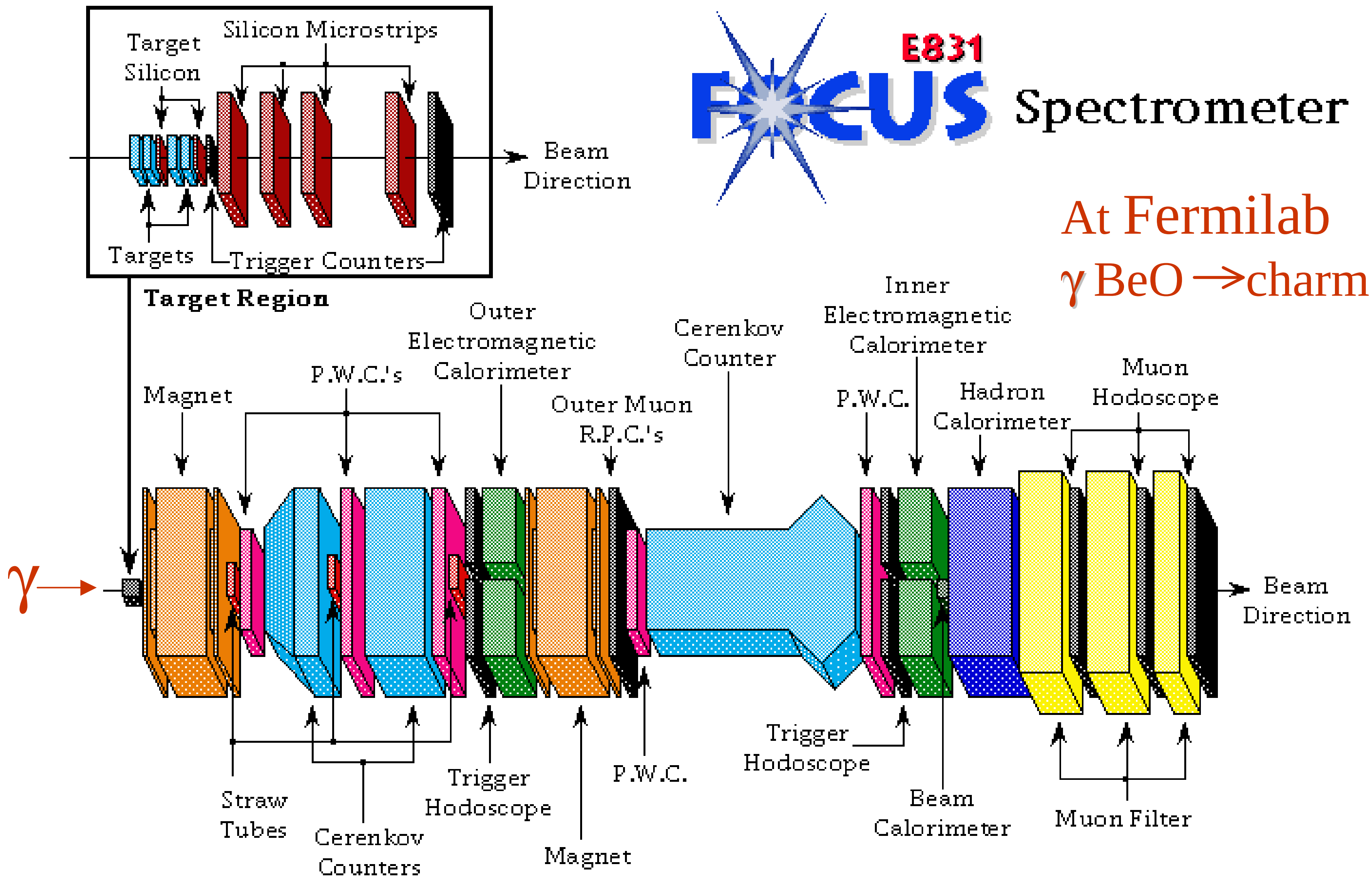
Charm Experiments: Fixed Target

- E791 – 1990/91
  - 500 GeV/c π^-
  - Target: Pt, C.
  - Follows: E516,E691,E769
- SELEX (E781) – ran 1996/97
  - 600 GeV/c π^-, Σ^-
  - 540 GeV/c p, π^+
  - Targets: C, Cu.
  - Goal: charmed baryons
- FOCUS (E831) – 1996/97
  - 300 GeV/c (max) γ
  - Target: BeO.
  - Upgraded E687.
- Will not include:
  - Charmonium: Fixed target, Tevatron, anti-p accumulator ring: E835.
  - Production physics.

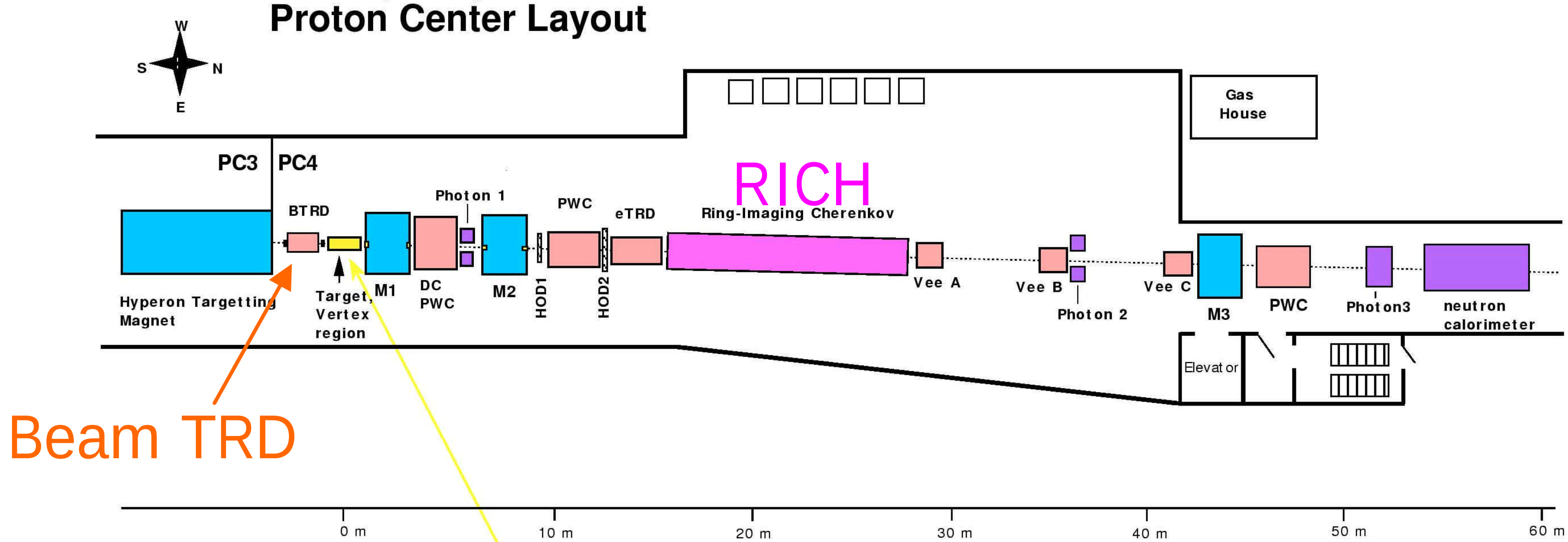
E831 FOCUS Spectrometer

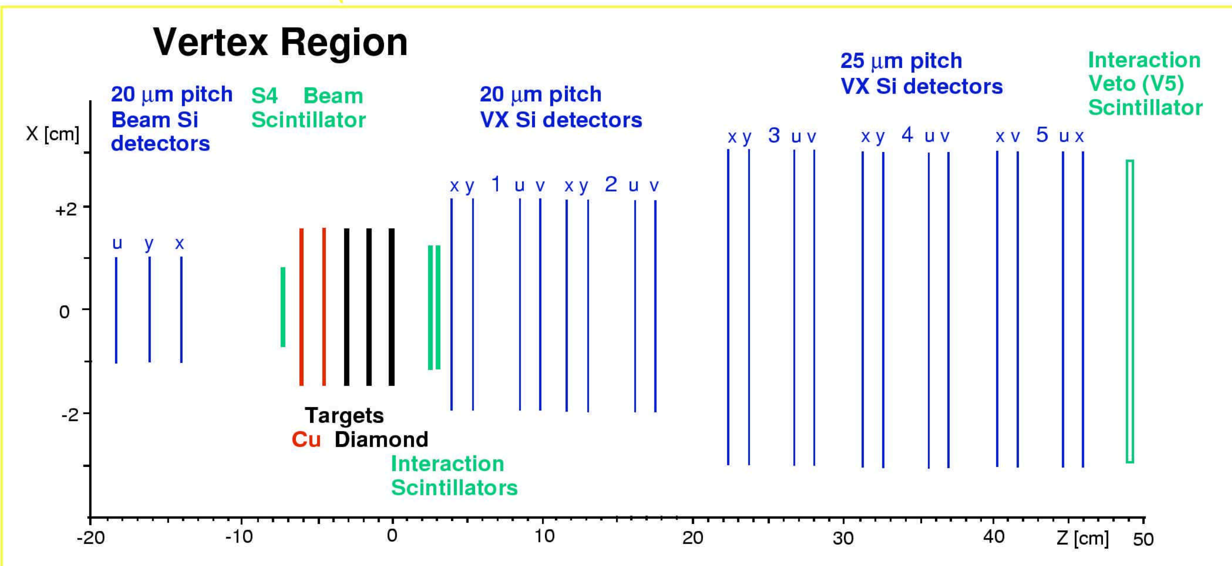
At Fermilab

γ BeO $\rightarrow$ charm



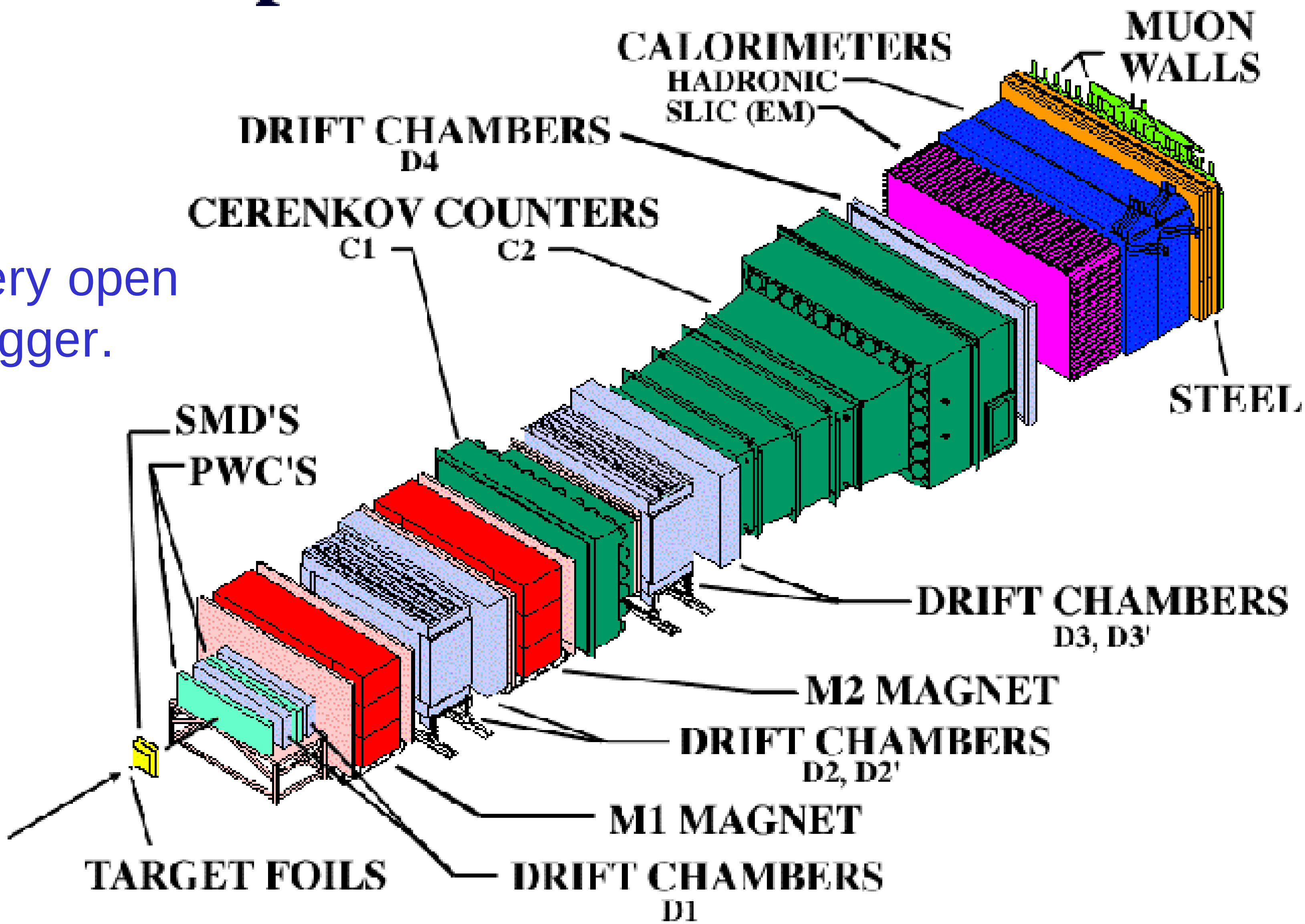
Selex (E781)
Proton Center Layout





E-791 Spectrometer

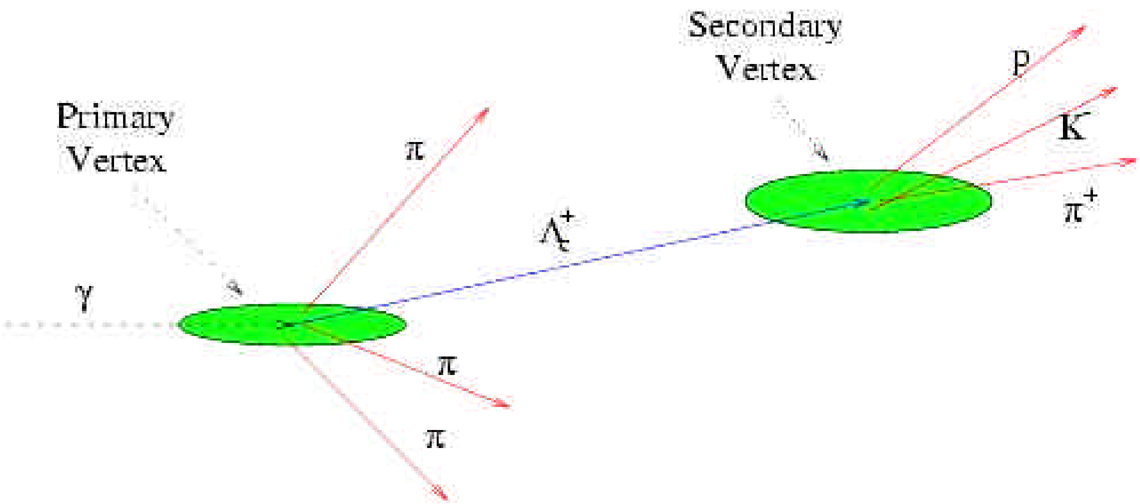
Very open trigger.



Properties of Fixed Target Exp ts.

- Segmented Targets
- Si μ-strip detectors
- Downstream magnets and tracking systems:
  - Momentum measurement
  - Vee s
- Cerenkov based PID
  - SELEX: RICH
  - FOCUS,791: Threshold
- EM Calorimetry:
  - FOCUS,SELEX: Pb Glass
  - E791: Pb liquid scint.
- Hadronic calorimetery.
- Muon chambers:
  - FOCUS, E791 only.
- High bandwidth trigger/daq.
  - 791: Very open trigger.
  - Others more selective.

Vertexing is the Key

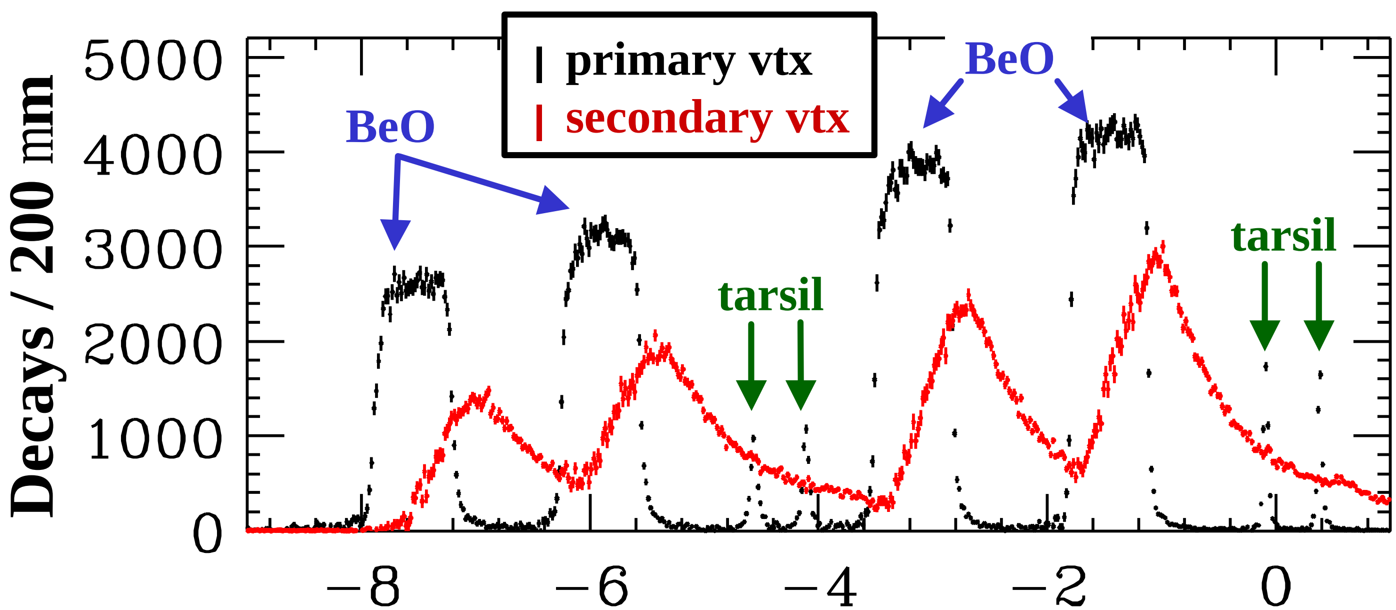


Golden Modes:

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^0 \rightarrow K^- \pi^+$

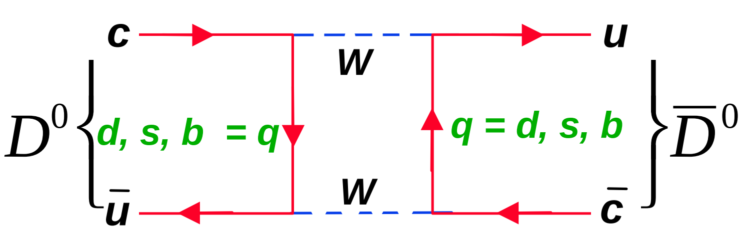
$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$



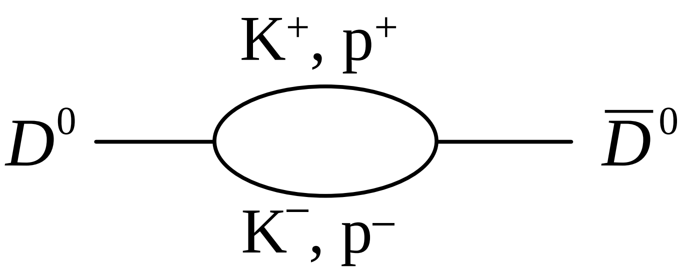
E831 FOCUS

Background Subtracted Golden Mode Charm

SM Expectations for D^0 Mixing



- Short distance effects from box diagram. Highly suppressed:
  - GIM mechanism



- Long distance effects from common intermediate states.

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix}$$

If CP is Conserved

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix}$$

Diagonalize this:

$$D_1^0 = \frac{1}{\sqrt{2}}\left(D^0 + \overline{D}^0\right) \qquad D_2^0 = \frac{1}{\sqrt{2}}\left(D^0 - \overline{D}^0\right)$$

These have definite mass and lifetime: M_1, M_2, Γ_1, Γ_2.

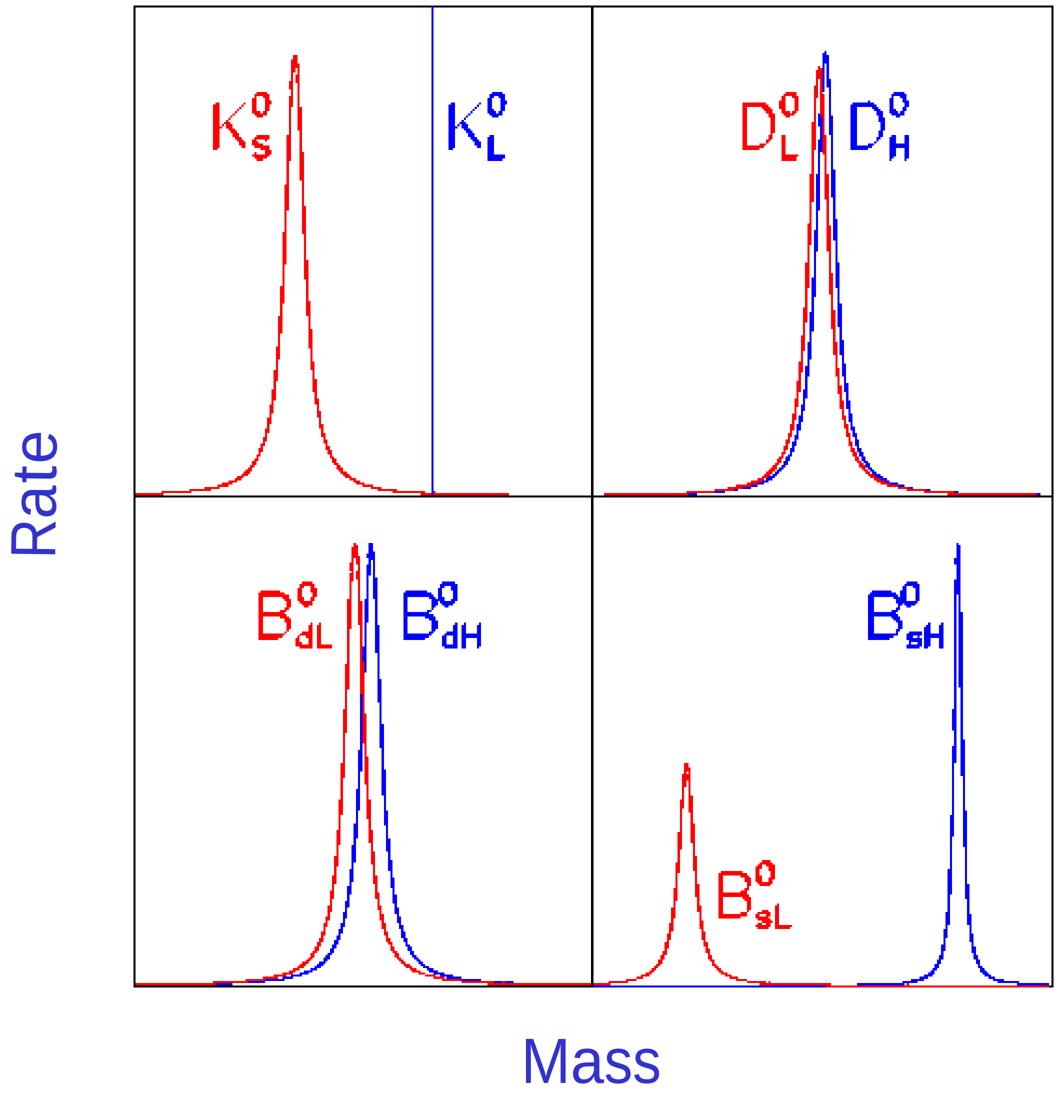
Define:

$$\Delta m = M_1 - M_2 \qquad \Gamma = \frac{(\Gamma_1 + \Gamma_2)}{2} \qquad \Delta\Gamma = \Gamma_2 - \Gamma_1$$

$$\boxed{x = \frac{\Delta m}{\Gamma}} \qquad \boxed{y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}}$$

Expt: $x < 0.03$ Expt: $-0.06 < y < 0.01$

Cartoon of Δm and $\Delta\Gamma$



Time Evolution

- $D^0 \to CP+$ (eg K^+K^-) $\quad \frac{dN}{dt} = \Gamma_1 \exp(-\Gamma_1 t)$
- $D^0 \to CP-$ $\quad \frac{dN}{dt} = \Gamma_2 \exp(-\Gamma_2 t)$
- $D^0 \to$ non-CP eigenstate (eg. $K^-\pi^+$, $K^-\mu^+\nu_\mu$)

$$\frac{dN}{dt} = \frac{1}{2}\left(\Gamma_1 \exp(-\Gamma_1 t) + \Gamma_2 \exp(-\Gamma_2 t)\right)$$
$$= \Gamma \exp(-\Gamma t)\left[\cosh(y\Gamma t) - y \sinh(y\Gamma t)\right]$$
$$= \Gamma \exp(-\Gamma t)\left[1 + O(y^2)\right]$$

Method 1: Compare lifetimes measured in K^+K^- and $K^-\pi^+$.
This measures y.

$D^0 \rightarrow K^- \mu^+ \nu_\mu$ Mixing

- Tag initial flavor using $D^{*+} \rightarrow D^0 \pi^+$.
- Look for "wrong sign" decays:
- SM expectation (expansion for small x and y):

$$r_{mix}(t) = \frac{1}{4} \Gamma^2 t^2 \exp(-\Gamma t)(x^2 + y^2)$$

- # of oscillations/mean lifetime = $x/2\pi$.

Method 2: Measure time dependence of wrong sign $K\mu\nu$.

$D^0 \to K^+\pi^-$: DCSD and Mixing

- DCSD: Doubly Cabbibo Suppressed Decay
- Wrong sign hadronic modes: both mixing and DCSD.

$$r_{WS}(t) = \frac{\Gamma\left(D^0 \to K^+ p^-\right)}{\Gamma\left(D^0 \to K^- p^+\right)}$$

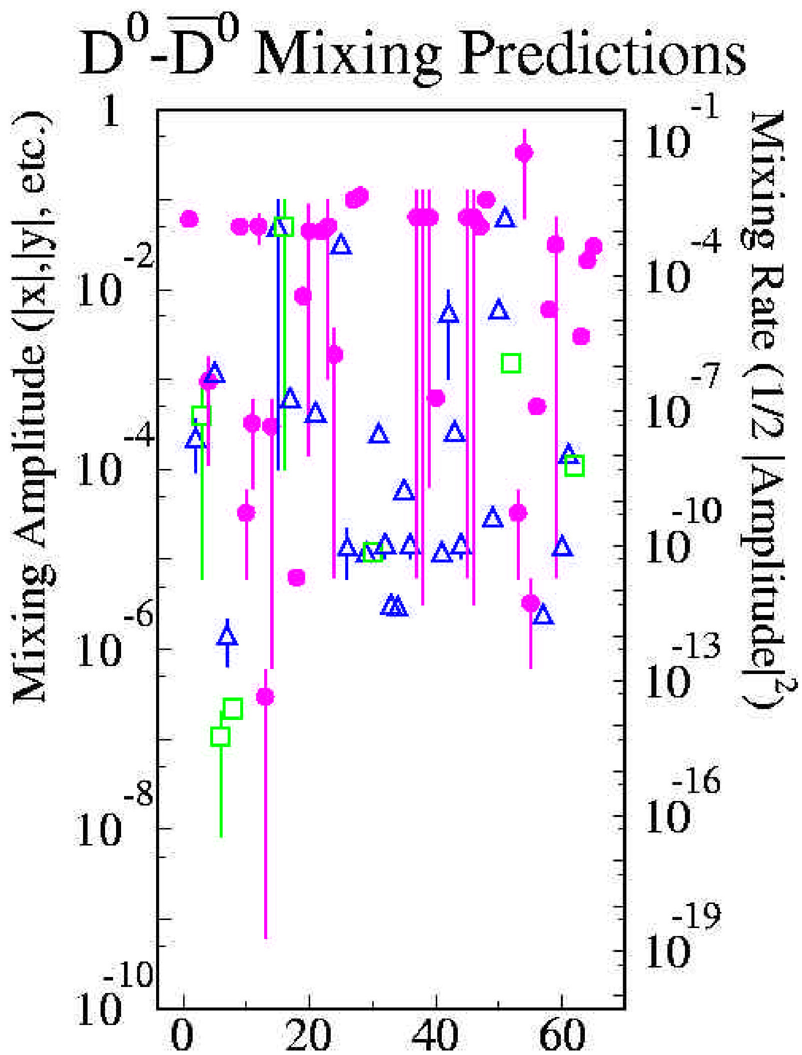
- SM prediction: $r_{WS}(t) = \left[r_{DCS} + \sqrt{r_{DCS}}\, y' t + \frac{\left(x'^2 + y'^2\right)}{4} t^2 \right]$

- t in units of mean lifetime; δ=relative phase between dcsd and mixing amplitudes.

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos d & \sin d \\ -\sin d & \cos d \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \qquad r_{DCS} = \frac{\Gamma_{DCSD}\left(D^0 \to K^+ p^-\right)}{\Gamma\left(D^0 \to K^- p^+\right)}$$

Method 3: Measure time dependence of wrong sign $K^+ \pi^-$:

Charm Mixing: Theory Predictions



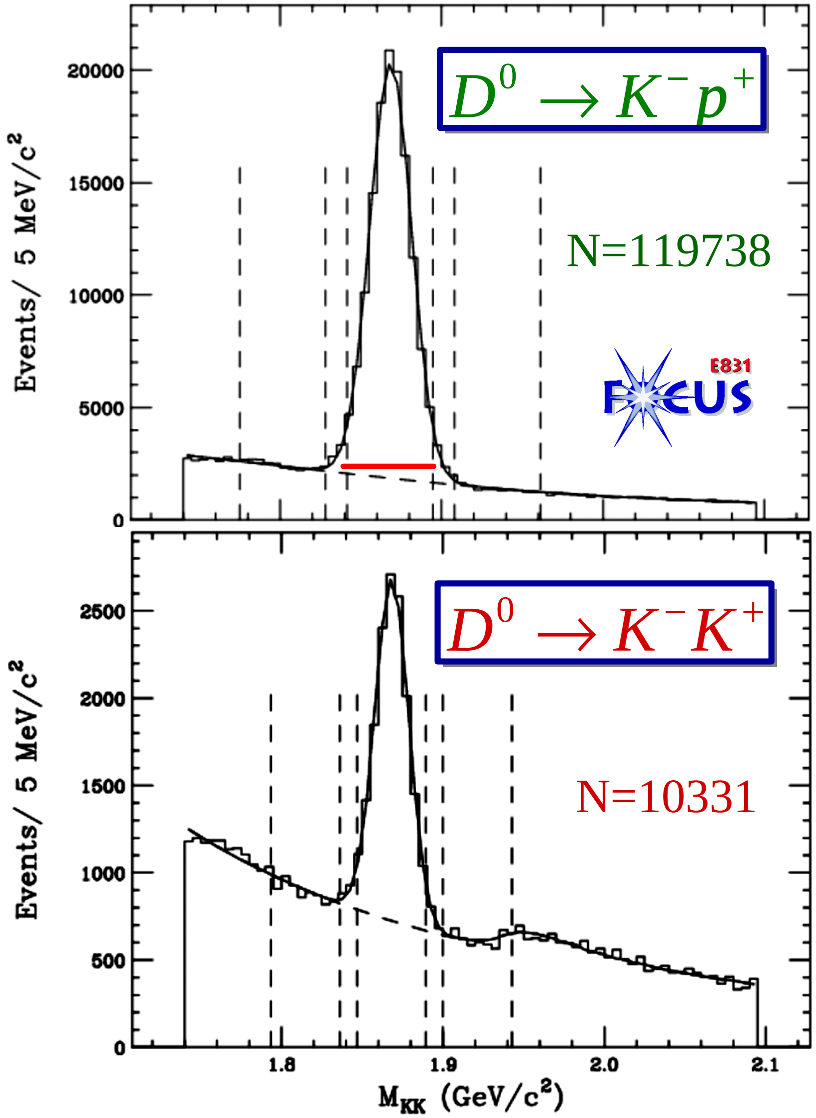
From compilation of H.N.Nelson hep-ex/9908021

Triangles are SM x
Squares are SM y
Circles are NSM x

Predictions encompass **15 orders magnitude** for R_{mix}

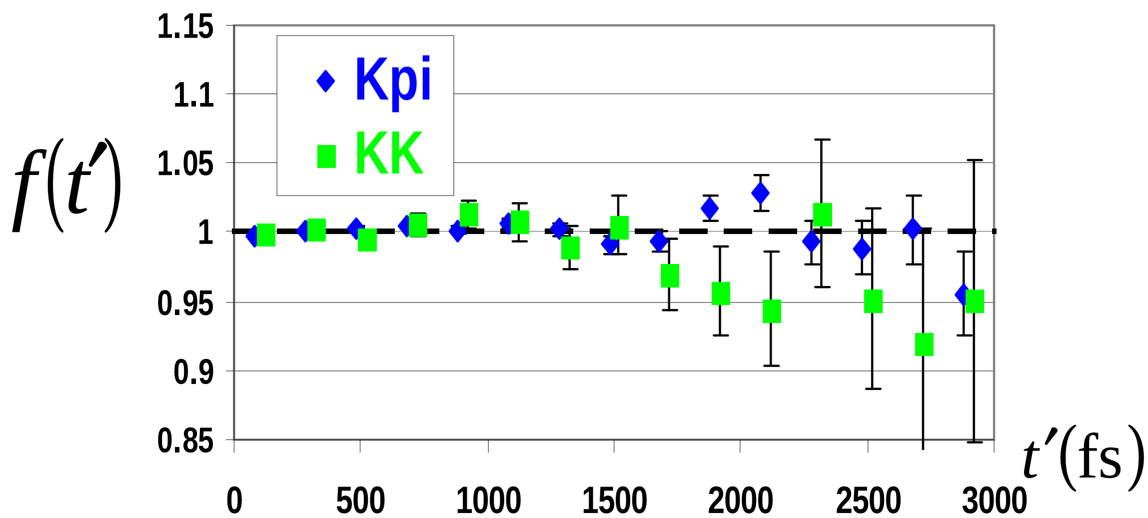
(but only 7 orders of x or y!)

FOCUS y_{CP} Measurement Phys. Lett. B485:62



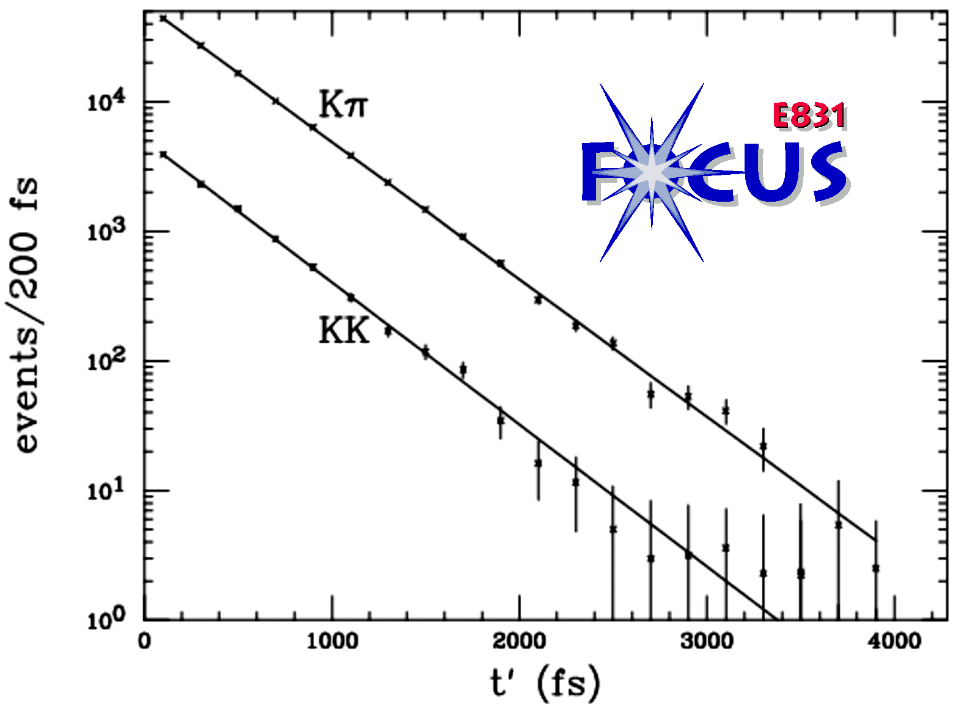
- Assumes CP invariance.
- y_{CP}=y if nature conserves CP
- $D^0 \rightarrow K^- K^+$: CP$^+$
- $D^0 \rightarrow K^- \pi^+$: 0.5 (CP$^+$+CP$^-$)
- Signal and sideband regions shown.
- Strong clean up and PID cuts.
- Slice into time bins, subtract BG and efficiency correct.
- Deal with reflections.

Acceptance Corrections: $f(t')$



- t'= (t – nσ), where n is the detachment cut.
- f(t') is very flat and is essentially same for K^-K^+ and $K^-\pi^+$.
- Derived from MC: fiducial volume, absorbtion.
- $\sigma(t') \cong 30$ fs: no need to convolute resolution.

FOCUS y_{CP} Measurement



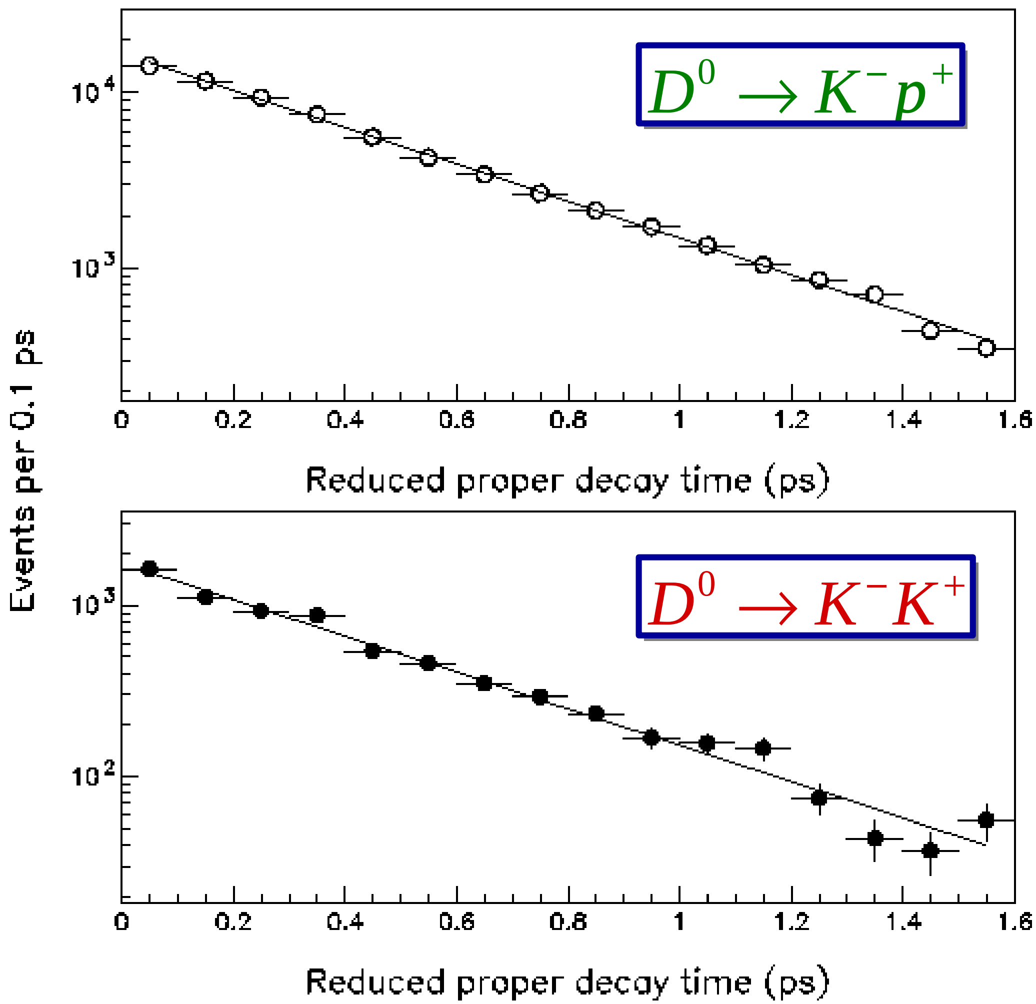
- Binned Max. Likelihood Fit
- Non-parametric treatment of the backgrounds.

$$y_{CP} = \frac{\Delta\Gamma}{2\Gamma} = \frac{t\left(K^- p^+\right)}{t\left(K^- K^+\right)} - 1$$

y_{CP} =(3.42 ± 1.39 ± 0.74)%

- Points: background subtracted, f(t′) corrected yields
- Lines: Fit results.
- $\tau(D^0)$ = 409.2 ± 1.3 (stat only); cuts optimized for y, not τ.

E791 y_{CP} Measurement



PRL. 83 (1999) p.32

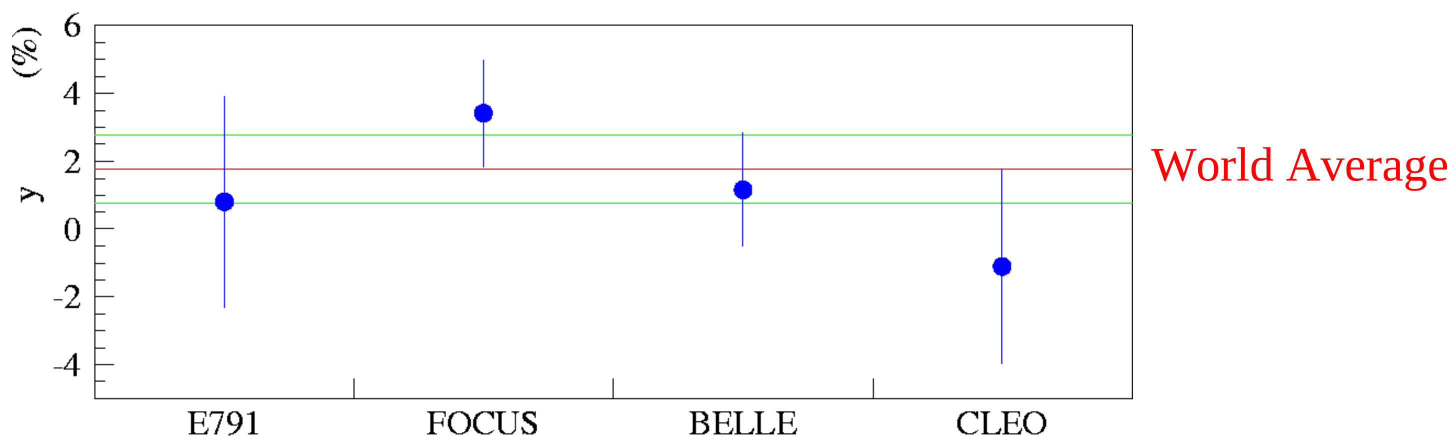
$$2(\Gamma_{KK} - \Gamma_{K\pi}) =$$

$$0.04 \pm 0.14 \pm 0.05 \text{ ps}^{-1}$$

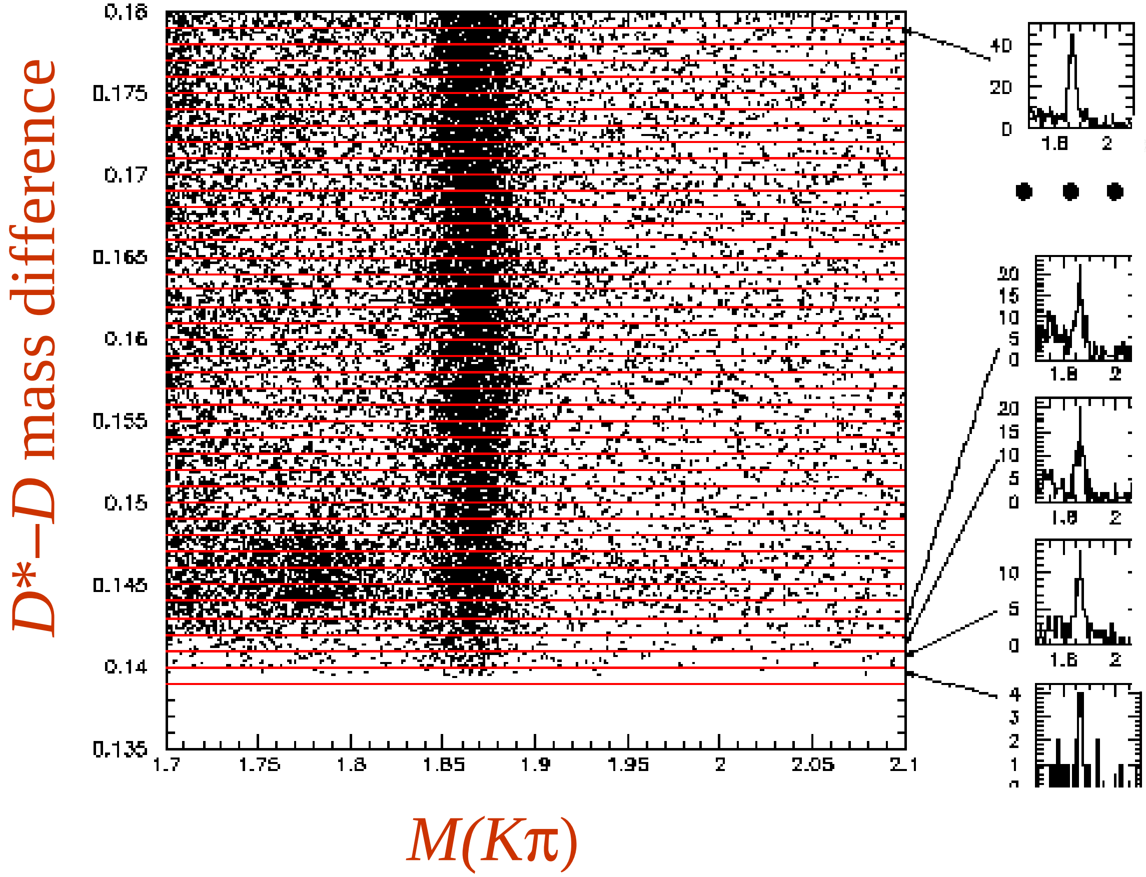
$$y_{CP} = (0.8 \pm 2.9 \pm 1.0)\%$$

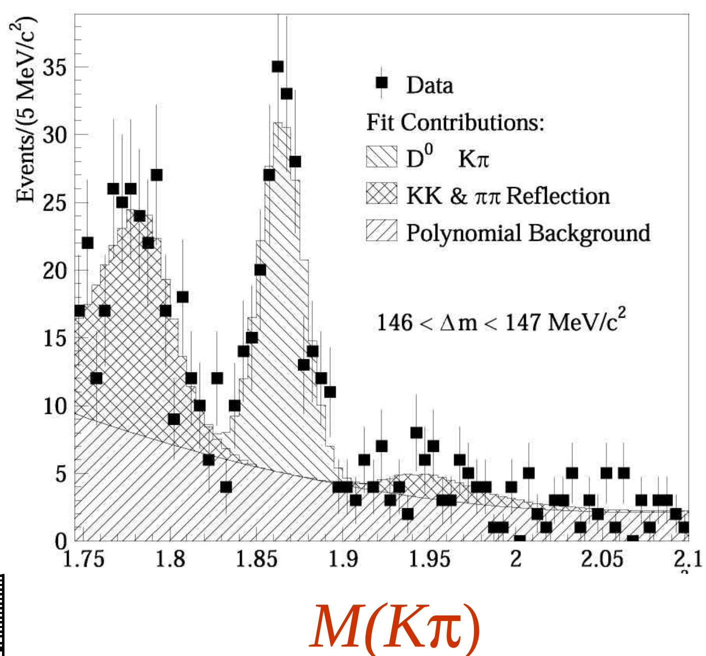
Comparison of y Results

Experiment	***y*** $_{\mathbf{CP}}$ **(%)**	**Lifetime D^0 g Kp (*fs*)**
E791	0.8 ± 2.9 ± 1.0	413 ± 3 ± 4
FOCUS	**3.42 ±1.39 ± 0.74**	**409.2 ± 1.3 (Stat. Only)**
BELLE (Preliminary)	$1.16^{+1.67}_{-1.65}$	414.5 ± 1.7 (Stat. Only)
CLEO (Preliminary)	–1.1 ± 2.5 ± 1.4	404.6 ± 3.6 (Stat. Only)
SELEX		407.9 ± 6.0 ± 4.3
World Average	1.77 ± 1.00	412.6 ± 2.8 (PDG 2K)



FOCUS: Wrong Sign $D^0 \to K^+\pi^-$

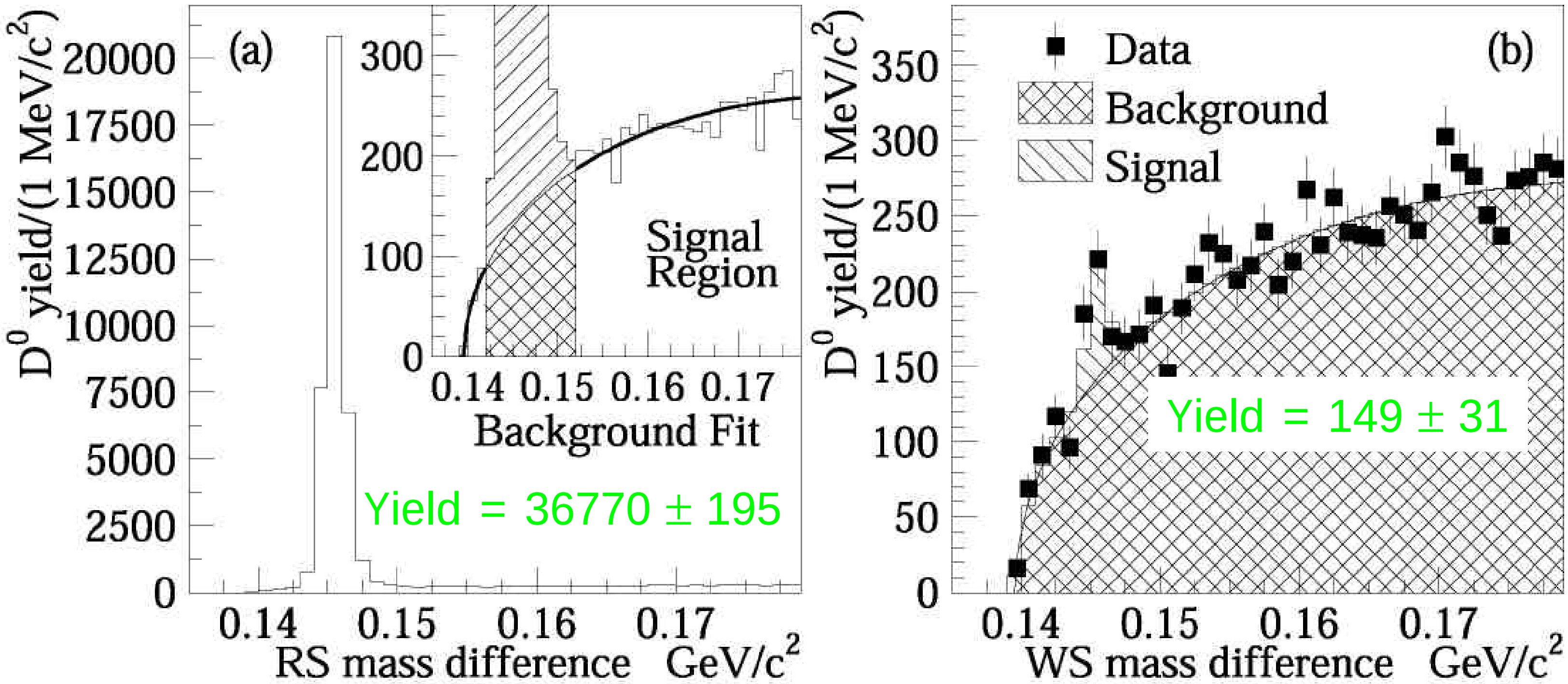




- Tight particle ID + extra hard cuts if $M(K\pi) \cong M(\pi K)$.

FOCUS R_{WS} Measurement

- Points: Fitted D^0 yield from previous page.



$$\text{FOCUS: } R_{ws} = (0.404 \pm 0.085 \pm 0.025)\%$$

$$\text{CLEO: } R_{ws} = (0.332^{+0.063}_{-0.065} \pm 0.040)\%$$

Interpretation of R_{WS} Measurement

$$r_{WS}(t) = \left[r_{DCS} + \sqrt{r_{DCS}}\, y'(t/t) + \frac{\left(x'^2 + y'^2\right)}{4} (t/t)^2 \right]$$

- Time integrated R_{WS} depends on detachment cuts!
  - Depends on t, not t.′
- Not a good observable: may vary between experiments!

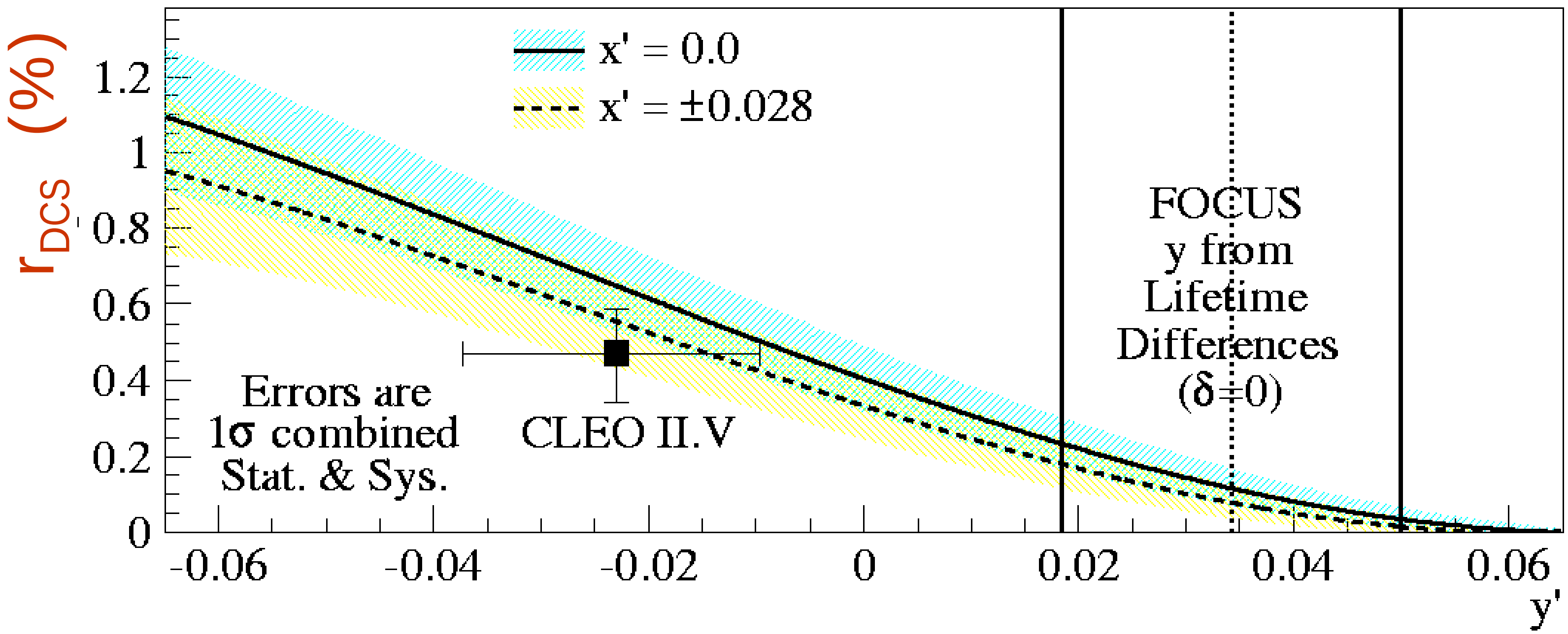
$$R_{WS} = r_{DCS} + \sqrt{r_{DCS}}\, y' \langle t/\mathrm{t} \rangle + \frac{\left(x'^2 + y'^2\right)}{4} \left\langle (t/\mathrm{t})^2 \right\rangle$$

- < > is average over true distribution of times.
- We believe x is small from semi-leptonic decays.
- Determine $\langle t/\tau \rangle$ and $\langle (t/\tau)^2 \rangle$ using MC
- Measure R_{WS} : 3 unknowns r_{DCS} , x', y' .

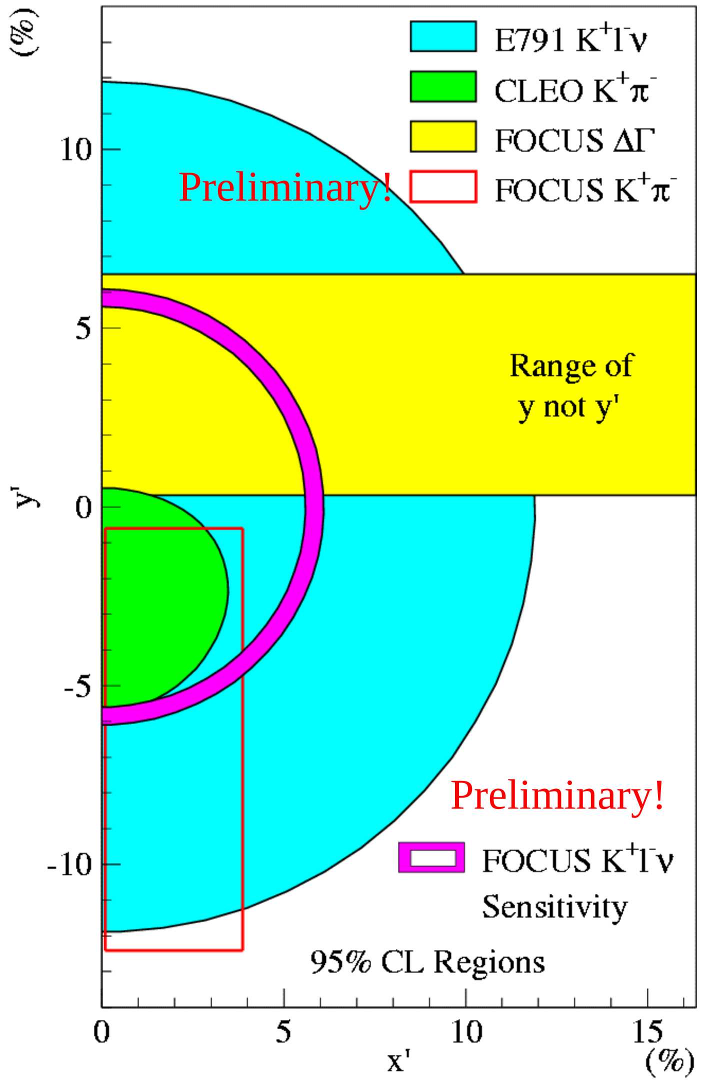
Interpretation of R_{WS} Measurement

$$R_{WS} = r_{DCS} + \sqrt{r_{DCS}}\, y' \langle t/\tau \rangle + \frac{(x'^2 + y'^2)}{4} \langle (t/\tau)^2 \rangle$$

•Using measured R_{WS} , for small x, solve for the allowed region in the r_{DCS} - y' plane.

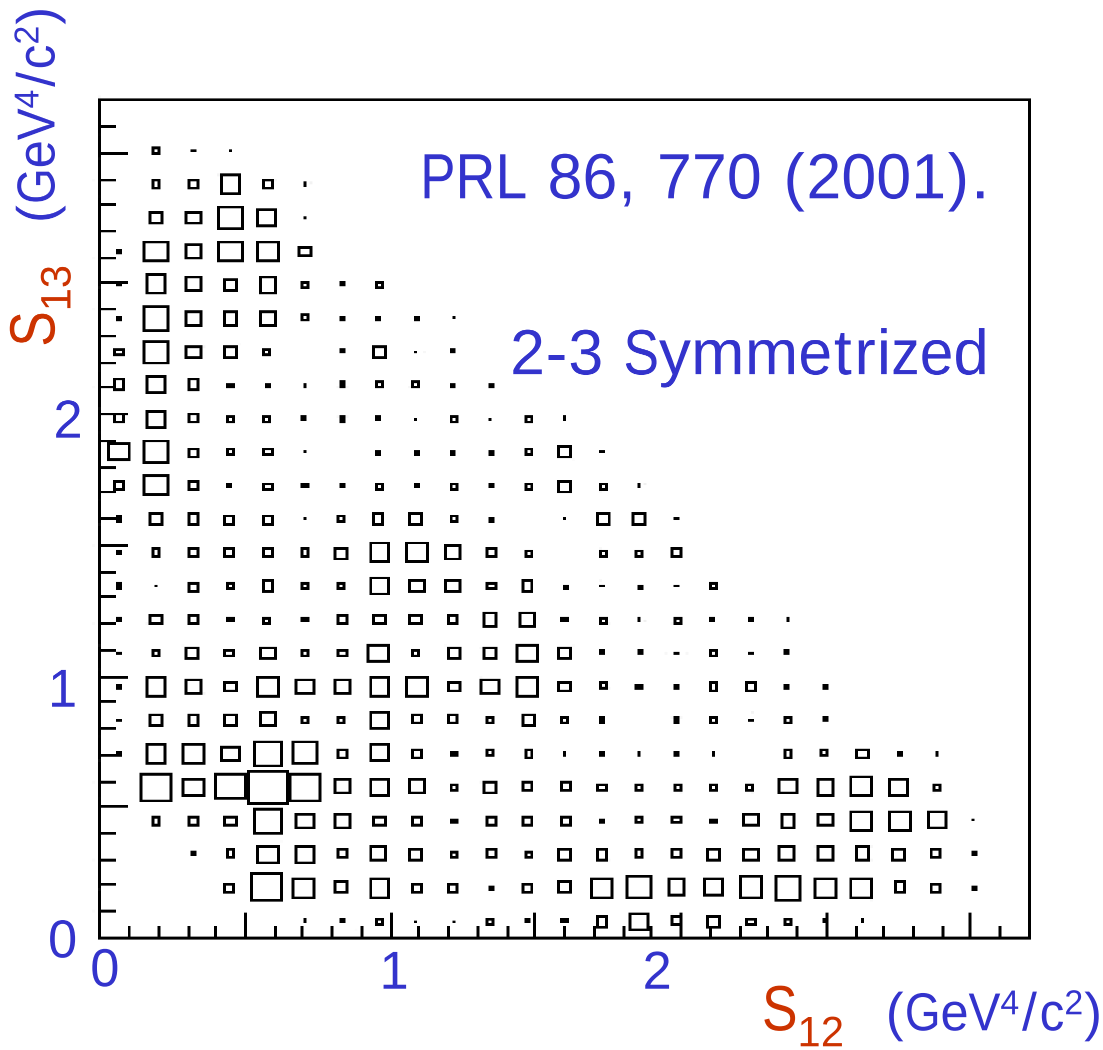


Comparison of Mixing Results



- No compelling signal.
- If δ is small, FOCUS y_{CP} can be compared directly to CLEO y'.
    - Both consistent with zero but they have opposite sign!
    - If opposite sign, implies large δ.
- Other measurements:
    - E791: $y_{CP} = (0.8 \pm 2.9 \pm 1.0)\%$
    - BELLE(prelim): $y_{CP} = 1.0^{+3.8}_{-3.5}{}^{+1.1}_{-2.1}$
    - E791 Klν: PRL 77:2384,1996.
    - CLEO: PRL 84:5038, 2000.

E791: $D^+ \to \pi^- \pi^+ \pi^+$ Dalitz Plot

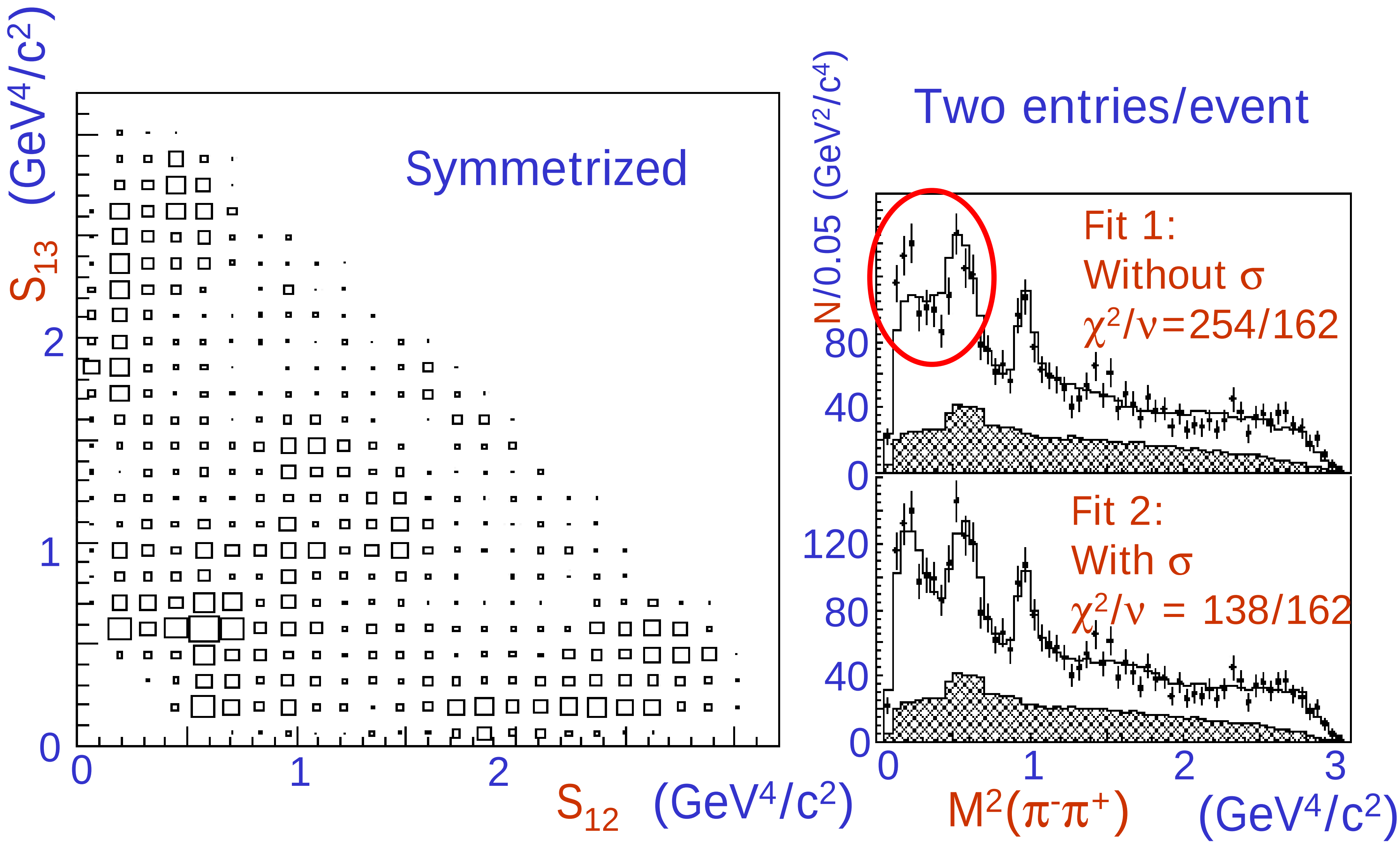


- Resonances included:

	Fit 1	Fit 2
$r^0 p^+$		
$f_0(980)p^+$		
$f_2(1270)p^+$		
$f_0(1370)p^+$		
$r^0(1450)p^+$		
Non-Resonant		
$\boxed{s p^+}$		

σ = Light Scalar

E791: Unbinned Max Likelihood Fit



Need a light isoscalar to fit the data: σ

	Fit 1	Fit 2
$\sigma\pi^+$	-	46.3 ± 9.0 ± 2.1
	-	205.7 ± 8.0 ± 5.2
$\rho\pi^+$	20.8 ± 2.4	33.6 ± 3.2 ± 2.2
	0. (fixed)	0. (fixed)
NR	38.6 ± 9.7	7.8 ± 6.0 ± 2.7
	150.1 ± 11.5	57.3 ± 19.5 ± 5.7
$f_0(980)\pi^+$	7.4 ± 1.4	6.2 ± 1.3 ± 0.4
	151.8 ± 16.0	165.0 ± 10.9 ± 3.4
$f_2(1270)\ \pi^+$	6.3 ± 1.9	19.4 ± 2.5 ± 0.4
	102.6 ± 16.0	57.3 ± 7.5 ± 2.9
$f_0(1370)\ \pi^+$	10.7 ± 3.1	2.3 ± 1.5 ± 0.8
	143.2 ± 9.7	105.4 ± 17.8 ± 0.6
$\rho^0\ (1450)\pi^+$	22.6 ± 3.7	0.7 ± 0.7 ± 0.3
	45.8 ± 14.9	319.1 ± 39.0 ± 10.9

Fit Fraction

Phase (degrees)

$M(\sigma) = 478 \pm 24 \pm 17$

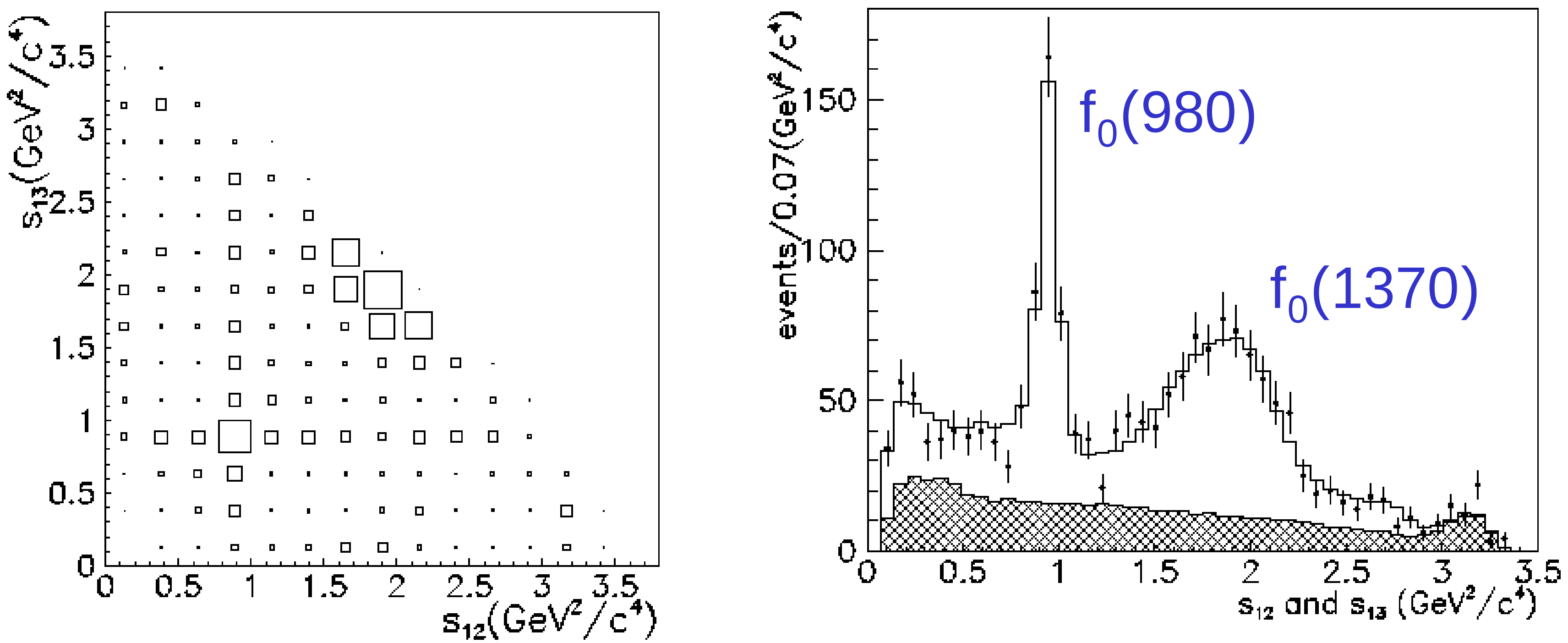
$\Gamma(\sigma) = 324 \pm 42 \pm 21$

both in MeV/c^2

Can other groups see it?

Is it in other channels?

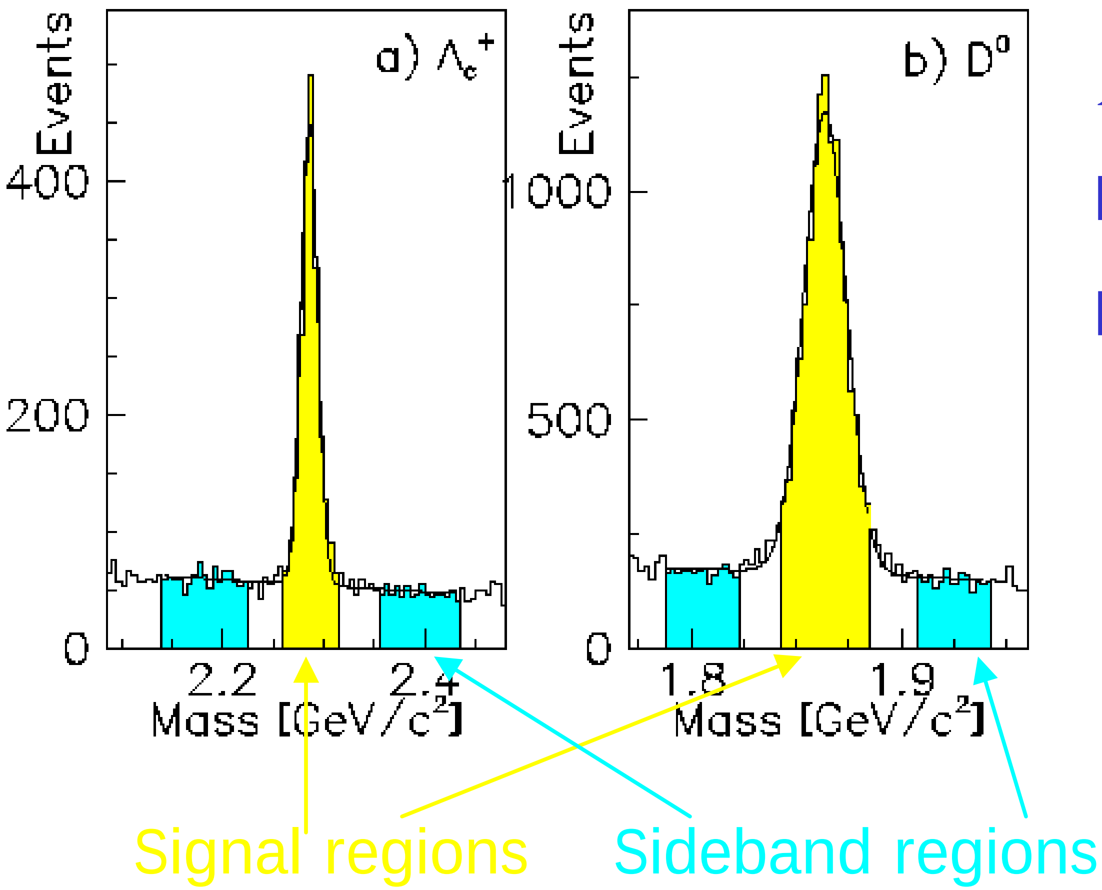
E791: $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ Dalitz plot



Phys. Rev. Lett. 86 (2001) p. 765.

- Other resonances present: $\rho^0(770)$, $\rho^0(1450)$, $f_2(1270)$.
- Mass and width measurements for the f(980) and f(1370).

SELEX: Λ_c and D^0 Lifetimes



$\Lambda_c^+ \to p\, K^- \pi^+$

$D^0 \to K^- \pi^+$

$D^0 \to K^- \pi^+ \pi^+ \pi^-$

+CC

No Λ_c^-

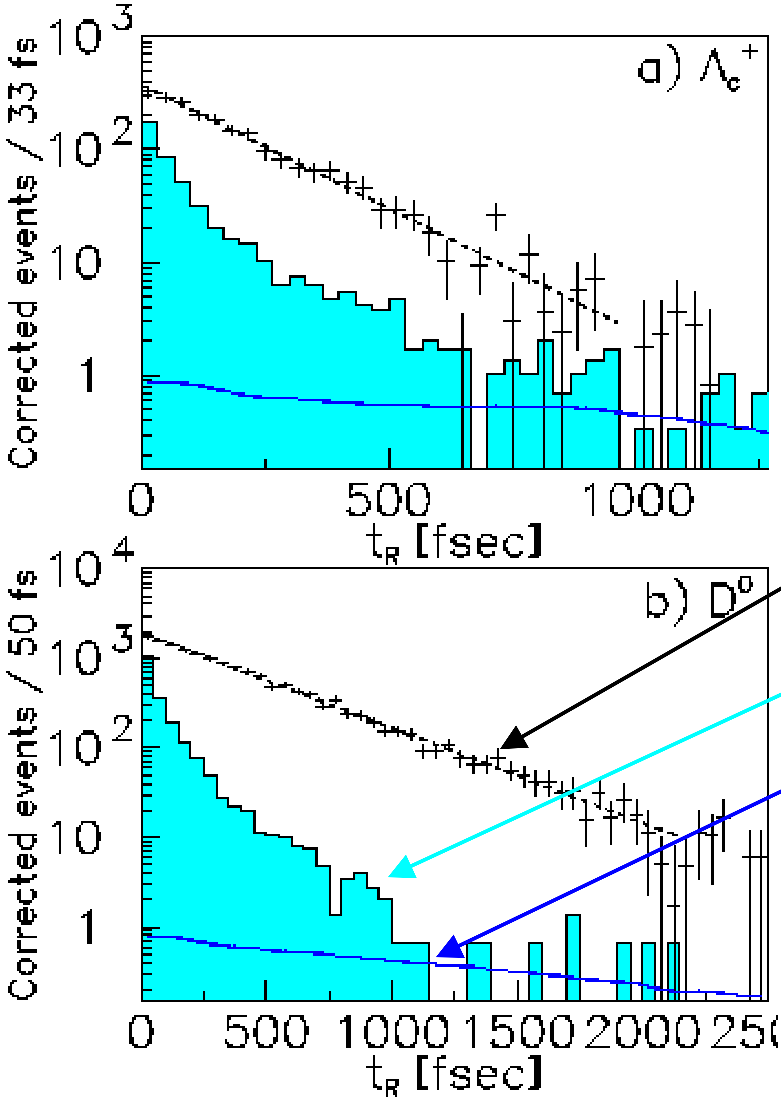
Reduced Proper time:

$t_R = [L-L_{Min}]\, M/pc$

$L_{Min} = 8\sigma_L$

Binned lifetime analysis OK since $\sigma(t_R) << \tau$.

SELEX: Λ_c and D^0 Lifetimes

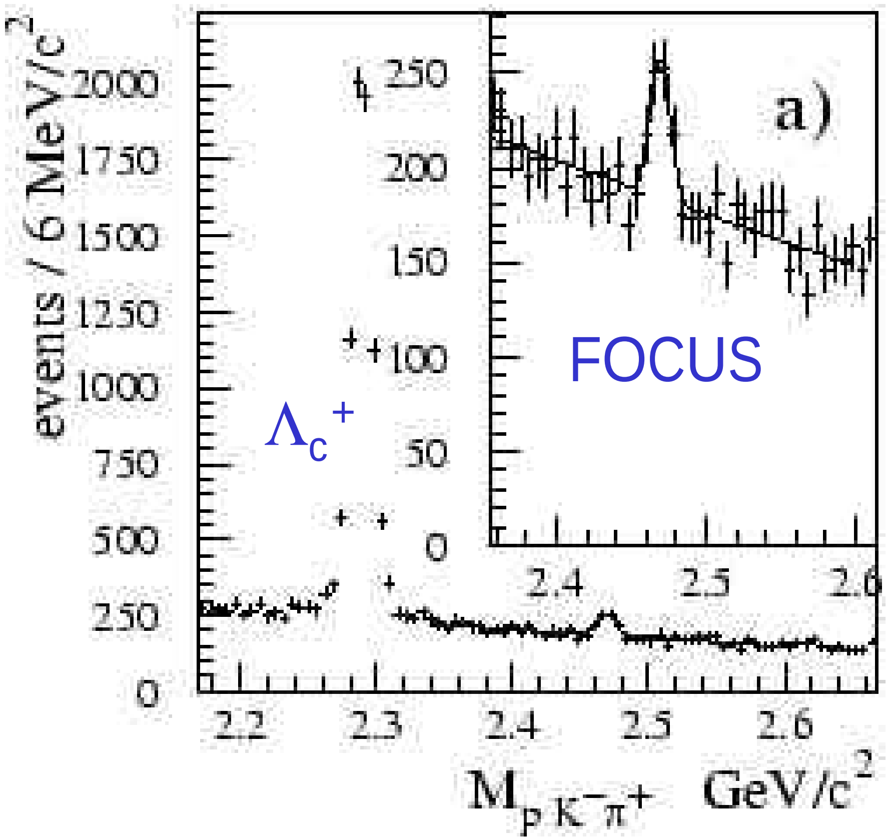


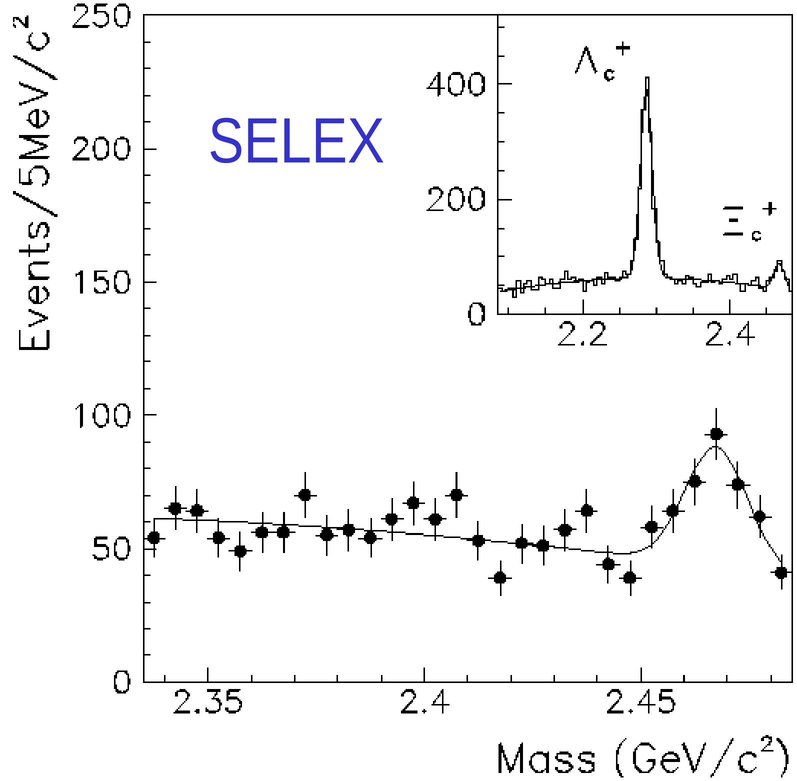
- Reduced Proper time: $t_R = [L-L_{MIN}]\ M/pc$
- Simultaneous Max Likelihood fit to the binned signal and sideband t_R distributions.
- BG sub, ε corrected data.
- Background
- Acceptance function.

$\tau(\Lambda_c) = 198.1 \pm 7.0 \pm 5.6$ fs

$\tau(D^0) = 407.9 \pm 6.0 \pm 4.3$ fs

Observation of $\Xi_c^+ \to pK^-\pi^+$





$$0.234 \pm 0.047 \pm 0.022 \quad = \frac{B(\Xi_c^+ \to pK^- p^+)}{B(\Xi_c^+ \to \Xi^- p^+ p^+)} = \quad 0.20 \pm 0.04 \pm 0.02$$

Additional Results: $\Xi_c^+ \rightarrow pK^- \pi^+$

FOCUS:

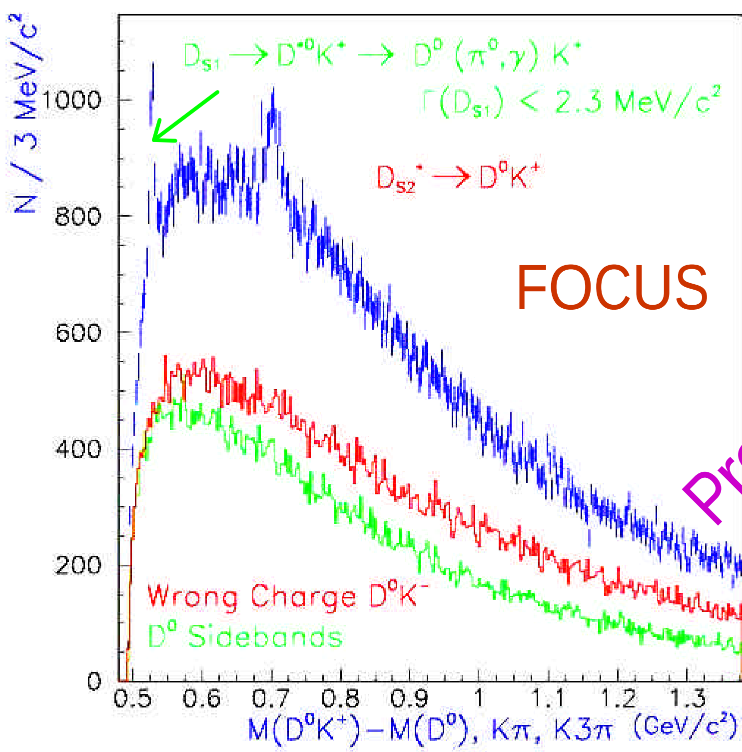
$$\frac{B(\Xi_c^+ \rightarrow p\overline{K}^*(892)^0)}{B(\Xi_c^+ \rightarrow pK^- p^+)} = 0.54 \pm 0.09 \pm 0.05$$

SELEX:

$$\frac{B(\Xi_c^+ \rightarrow pK^- p^+)}{B(\Xi_c^+ \rightarrow \Sigma^+ K^- p^+)} = 0.22 \pm 0.06 \pm 0.03$$

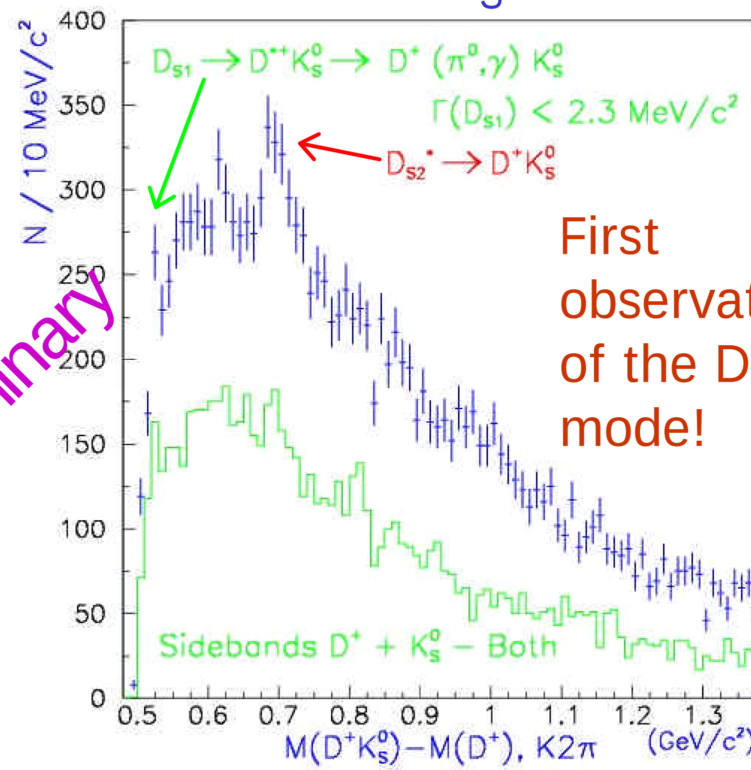
Observation of the D_{s2}^* at Focus

D^0K^+



Preliminary

$D^+K_S^0$

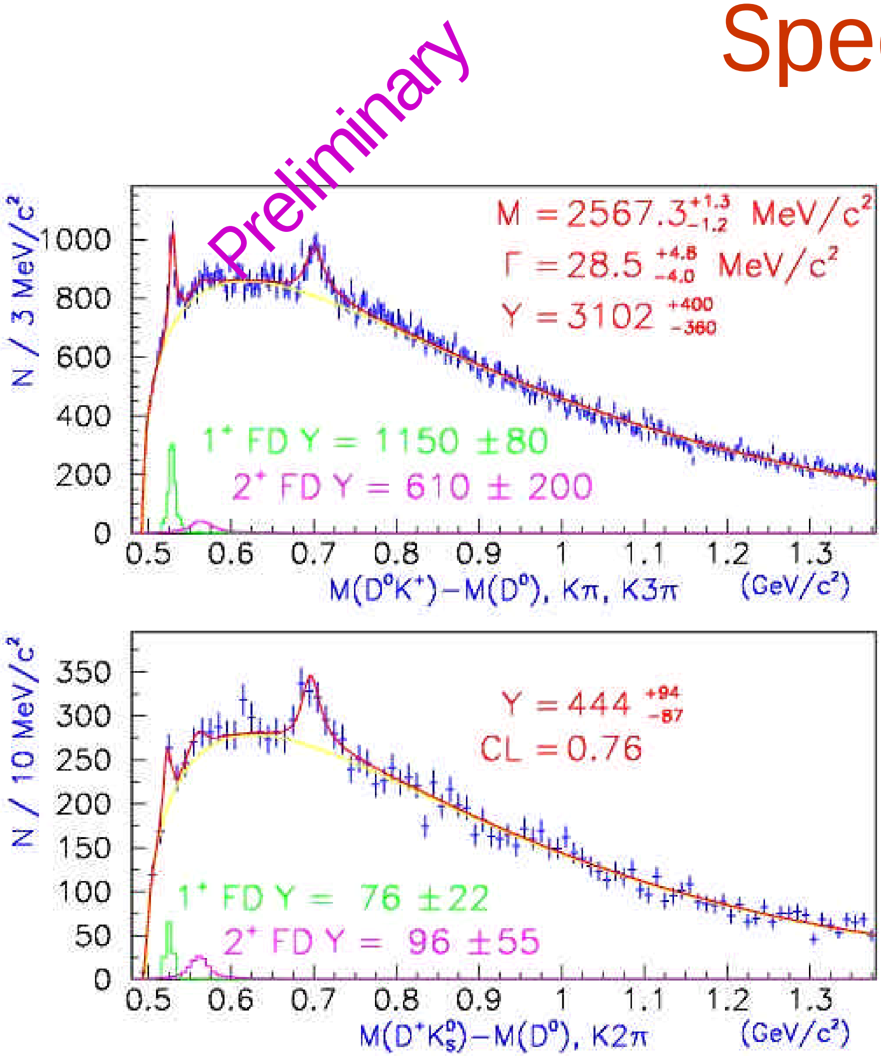


First observation of the $D^+K_S^0$ mode!

D_{s2}^* has L=1 between quarks.

There are some real K_S^0 in the sideband sample.

Simultaneous Fits to D^0K^+ and $D^+K_S^0$ Spectra



First observation of $D^+K_S^0$ mode

Terms in the fit:

1. D_{S2} Signal: D-wave Rel. BW
2. Smooth background shape
3. MC D_{S1} feeddown shape
4. MC D_{S2} feeddown shape. Significance is not stable with cut variations!

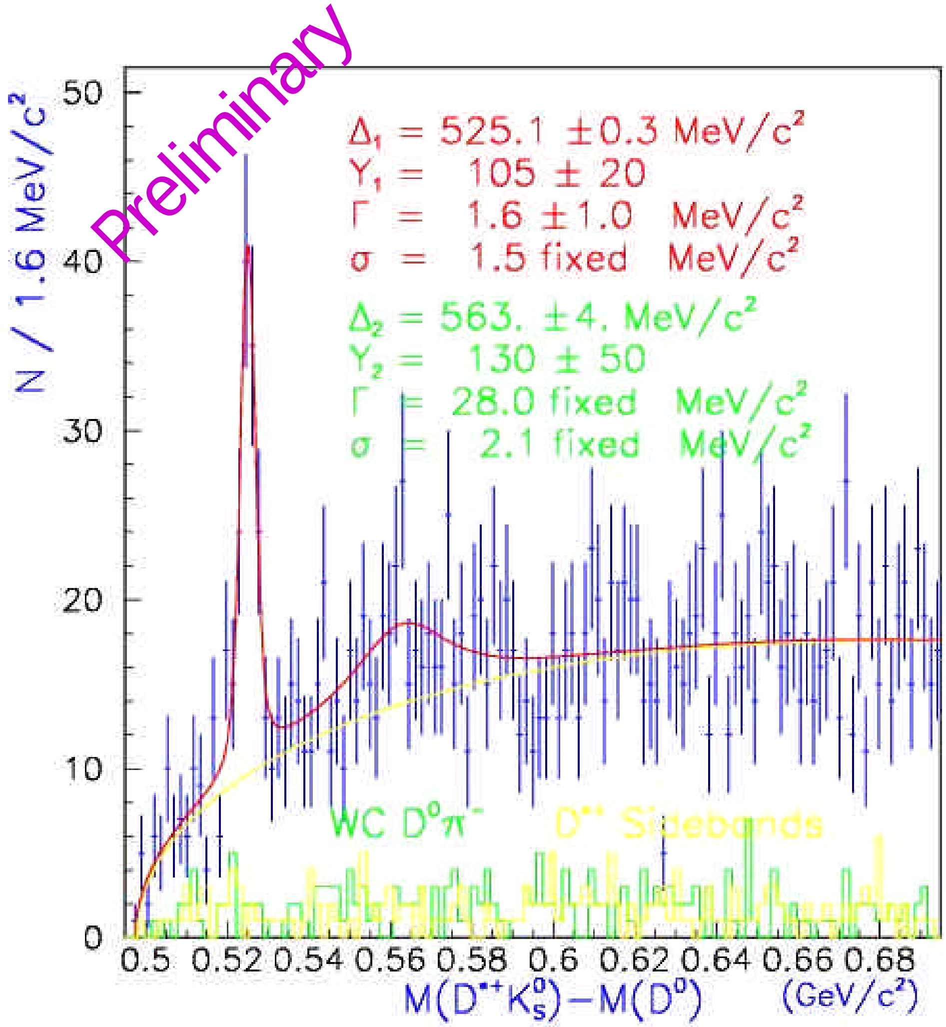
- Simultaneous: M and Γ same.
- Errors are statistical only

PDG:

$M = 2573.5 \pm 1.7$ MeV/c^2

$\Gamma = 15 \pm 5$ MeV/c^2

Observation of the D_{S1} at FOCUS



Terms in the fit:

1. D_{S1} Signal: Non Rel BW, convoluted with a gaussian.
2. Smooth background shape.
3. D_{S2}^* Signal: D-wave Rel BW.

- Errors are statistical only

PDG:

$\Delta = 525.35 \pm 0.34$ MeV/c^2

$\Gamma < 2.3$ MeV/c^2 @ 90 % CL.

Charm Summary

- E791 still going strong 10 years after data taking.
  - Weak decays, production, strong interaction physics in Dalitz plots, rare decay physics.
- FOCUS and SELEX are now starting to publish.
  - Expect lots more to come: lifetimes, Dalitz plots, charm spectroscopy, mixing and DCSD, rare decays, production ...
- One recent highlight is the new level of precision available for measurements of mixing and DCSD.
  - If it's real, it's interesting.

B Physics at CDF in Run I

- $\sin 2\beta = 0.79^{+0.41}_{-0.44}$.
- First fully reconstructed B_s.
- Measurements of mixing in B_d sector.
- Limits on mixing in the B_s sector:
- Amplitude analysis of $B^0 \rightarrow J/\psi\ K^{*0}$ and $B_s \rightarrow J/\psi\ \varphi$.
- Lifetimes: B^+, B^0, B_s, Λ_b.
- First observation of B_c.
- Production cross-section and differential cross-sections.

B Physics at CDF in Run I ...

- Limits on rare decays.
- Onia production.
- b quark fragmentation functions.
- J/ψ and χ_c, both prompt and from B's.

B Physics at D0 in Run I

- Limits on rare decays.
- Production cross-section and differential cross-sections.
- J/ψ, both prompt and from B's.

B Physics at the Tevatron: Run II…

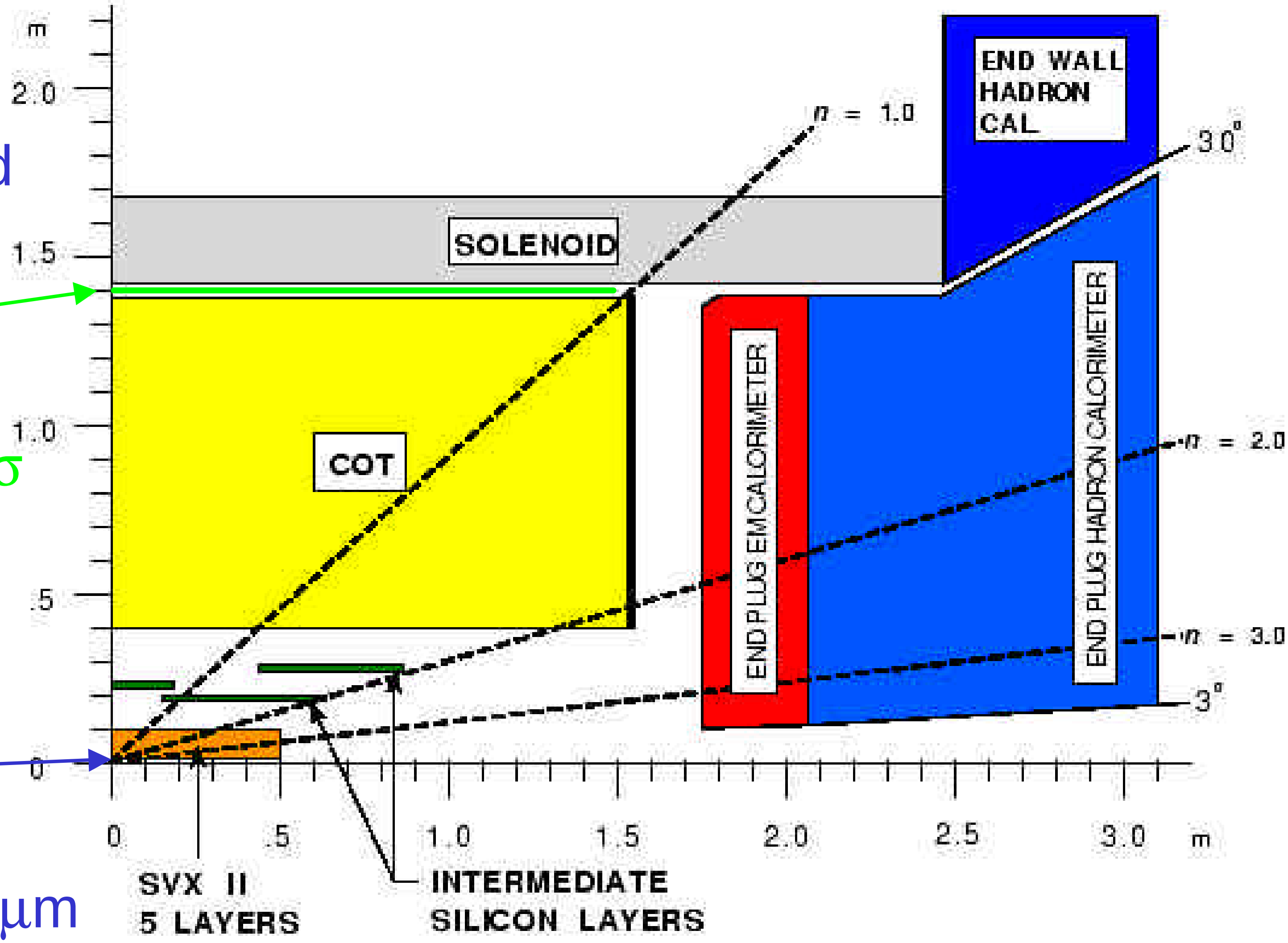
- Commissioning runs started in March 2001.
  - Goal: start real data taking Sept. 2001.
  - Will run until significant lumi at LHC (15 fb^{-1} ?).
- Huge luminosity upgrade
  - Run I: $\approx$100. pb^{-1} best year
  - Run II: 2000. pb^{-1}/year (design lumi)
- Upgraded detectors CDF and D0:
- Main physics goals: Higgs, SUSY, Precision top, etc
  - These require excellent b tagging.
  - B physics is an important part of these programs
- New dedicated B detector $\approx$2006: BTeV
- Workshop: http://www-theory.fnal.gov/people/ligeti/Brun2/

CDF Run II Upgrades

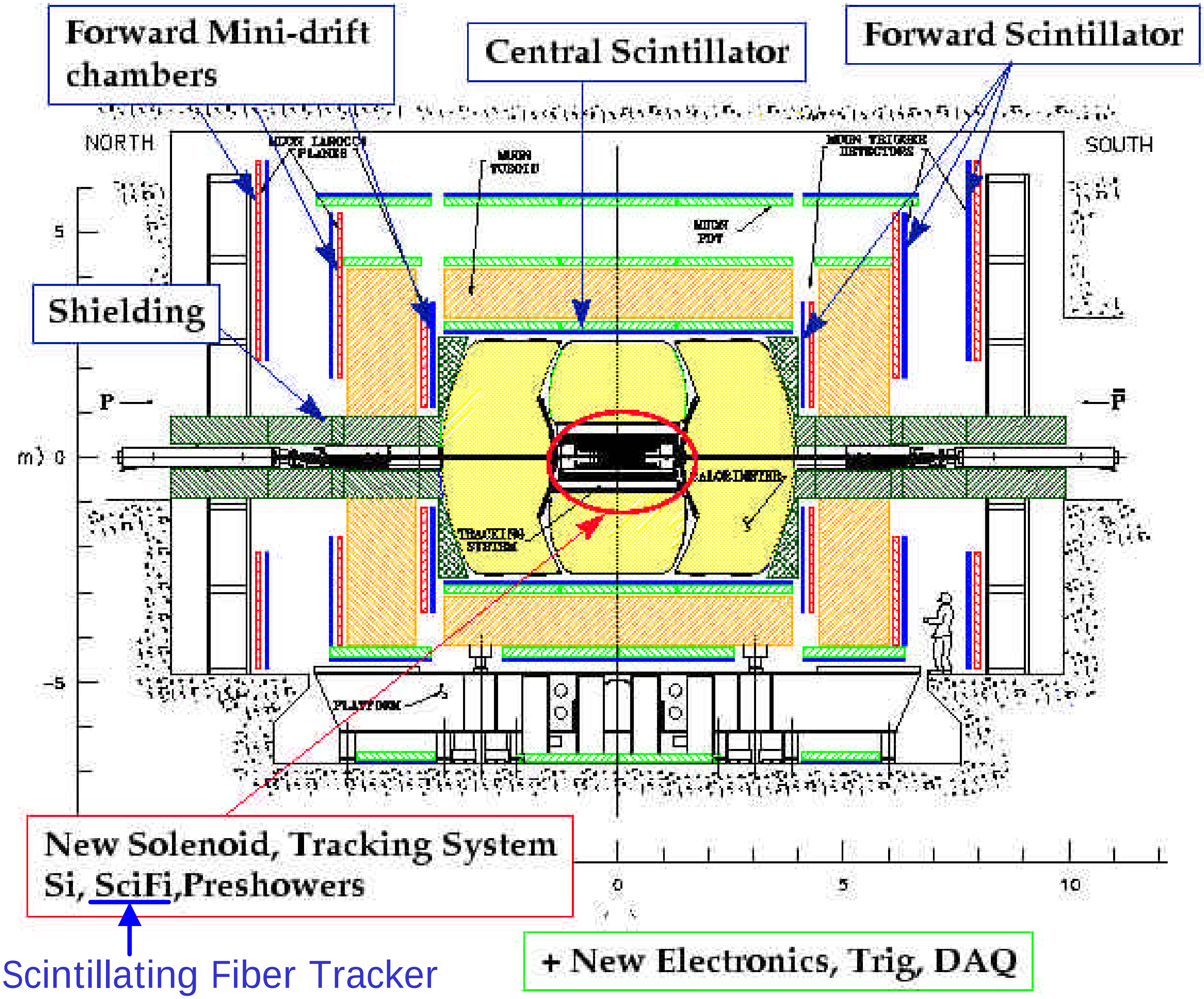
Electronics, Trigger and DAQ upgraded

TOF:
σ_t= 25 ps
K/π Sep. at 2σ to 1.6 GeV/c

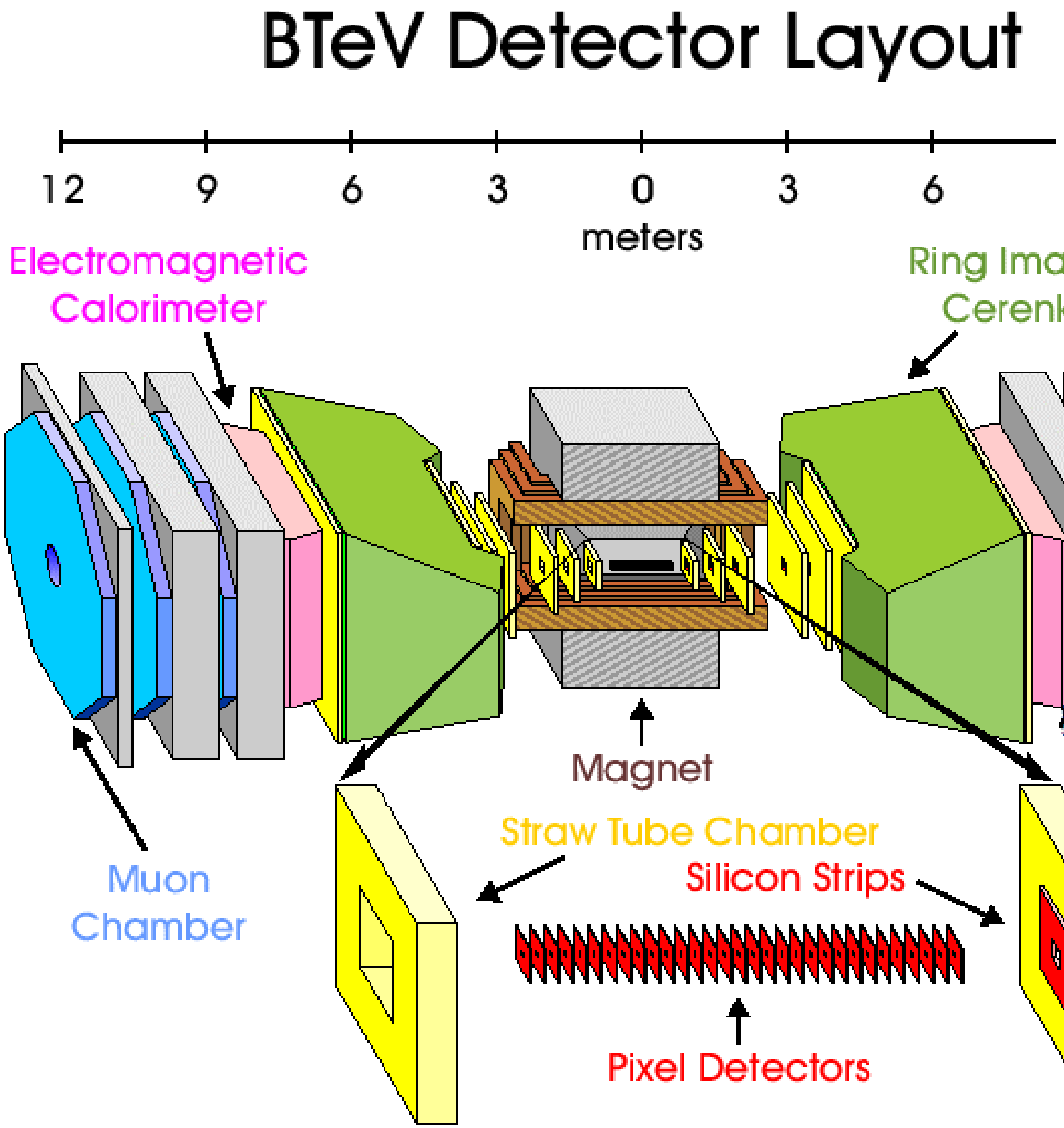
Layer 00 on beam pipe
σ_b: 50μm$\rightarrow$35μm



D0 Upgrade



Forward Mini-drift chambers
Central Scintillator
Forward Scintillator
Shielding
NORTH
SOUTH
MUON TOROID
MUON PDT
CALORIMETER
TRACKING SYSTEM
PLATFORM
P
P̄
5
0
-5
10
New Solenoid, Tracking System
Si, SciFi,Preshowers
Scintillating Fiber Tracker
+ New Electronics, Trig, DAQ



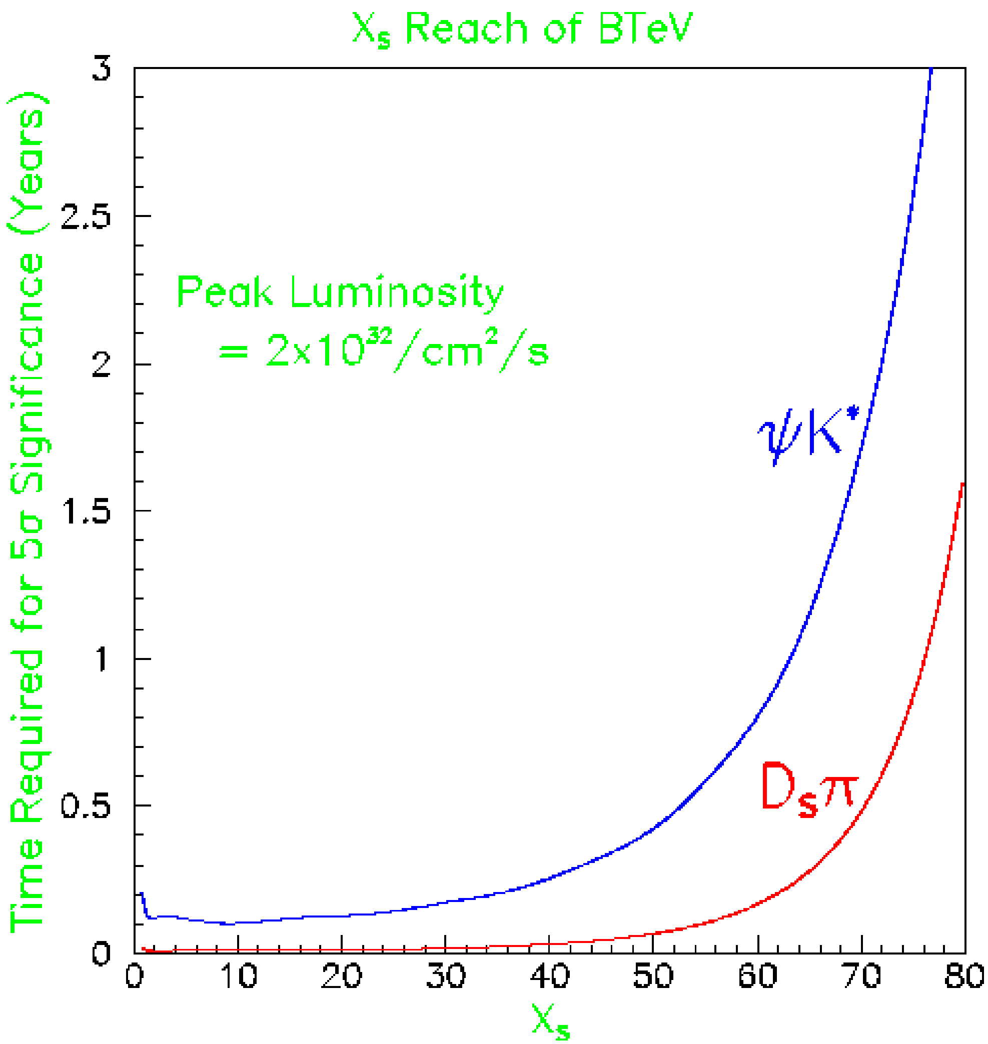
Stage I approval received June 2000.

2^{ndry} vertex trigger at Level 1

Some Comparisons

- Compare to e^+e^- B-factories:
  - \+ About 4 orders of magnitude more rate.
  - \+ Access to B_s, B_c, and b baryons.
  - \- Poorer S/B; at e^+e^- initial state well understood.
- BTeV vs CDF and D0:
  - \+ BTeV is a dedicated b experiment.
  - \+ Much better K/π/p particle ID.
  - ± More aggressive trigger.
  - \- CDF and D0 are running now.

Sensitivity to B_s Mixing



- CDF has sensitivity out to ≈60 for 2 fb^{-1}.
- D0 has sensitivity out to ≈30, for 2 fb^{-1}.

This will be one of the first important b physics measurements of Run II.

$\sigma(x_s) \approx 0.2$ for all interesting values of x_s .

Other Projections for 2 fb^{-1}

- CDF: Errors on B^-, B^0, B_s and Λ_b lifetimes will decrease 5x.
- B_s lifetime difference
  - CDF: $B_s \to J/\psi\phi$ and $D_s^{(*)+}D_s^{(*)-}$

$$s\left(\frac{\Delta\Gamma_s}{\Gamma_s}\right) = 0.04$$

  - BTeV: $B_s \to J/\psi\eta^{(\prime)}$, $J/\psi\pi$, $D_s\,\pi$

$$s\left(\frac{\Delta\Gamma_s}{\Gamma_s}\right) = 0.02$$

- $\sigma(\sin 2\beta) = \pm 0.05$ (CDF,D0)

  $\sigma(\sin 2\beta) = \pm 0.025$ (BTeV)
  - BaBar now $= \pm 0.2$ stat
  - Projects to ± 0.04 stat for 500 fb^{-1} at PEP II.
- $B_s \to D_sK$
  - CDF: $\sigma(\sin(\gamma+\delta)) = 0.4$–$0.7$ (± 0.1 by end of Run II)
  - BTeV: $\sigma(\gamma) = \pm 7^{o}$

Other Projections for 2 fb^{-1}

- $B^0 \rightarrow \pi^+\pi^-\pi^0$ $(\rho\pi)$
  - BTeV: O(1000) diluted flavor tagged events.
  - Compares to a few tens for B-factory at their design lumi.
  - BTeV: Learning how to do Dalitz plot fits with resolution effects, efficiency and backgrounds.

- $B_s \rightarrow J/\psi\eta^{(\prime)}$:

  $\sigma(\sin 2\beta_s) = \pm 0.03$ (BTeV)

  CDF looking at this too.

- BTeV: a lot of charm will pass the b trigger. High precision measurments, or limits, on x, y, r_{DCS}, rare decays.

- CDF and D0 have not evaluated how much charm they get.

B Physics at the Tevatron Summary

- During Run I B physics was an afterthought but it still produced a wealth of B physics, competitive in many places with CLEO, LEP, SLD.
- Run II detectors have B physics designed in.
- Great things are expected. Will be competitive with the B-factories in many areas and will exceed them in others.
- BTeV will come online near the end of Run II and will carry the B physics program to the end of the decade. It will also have a signficant charm program.